TECHNICAL REPORT VU-66-1

AIR FORCE TECHNICAL APPLICATIONS CENTER
HEADQUARTERS UNITED STATES AIR FORCE
WASHINGTON DC 20333

LONG RANGE SEISMIC DATA FROM THE LAKE SUPERIOR SEISMIC EXPERIMENT 1963-1964

31 MARCH 66

PREPARED FOR
ARPA PROJECT *VELA-UNIFORM*

BY

AF TECHNICAL APPLICATIONS CENTER
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AFTAC/VELA SEISMOLOGICAL CENTER
TECHNICAL REPORT VU-66-1
PROJECT VELA-UNIFORM
31 MARCH 1966

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ABSTRACT

As part of a planned subcrustal experiment, three series of chemical explosions, ranging in size from 1/8 ton to 10 tons, were detonated on the bottom of Lake Superior during July 1963 and July and October 1964. Although these explosions were intended primarily for stations deployed at fairly close distances, many of them were detected at distances of approximately 500 to 2500 kilometers during routine daily recording operations at a number of mobile Long Range Seismic Measurements van stations, at five experimental seismic observatories, and at several scattered deep-well installations, all operated as part of a VELA-UNIFORM research program under the technical direction of the Air Force Technical Applications Center.

This report summarizes the types of data recorded, presents typical measurements, and discusses some of the resulting conclusions. Travel times of Pn and P, S, Lg, and some unidentified emergent phases were measured. Residuals of Pn and P with reference to a constant velocity of 8.1 kilometers per second are compared with results from the Nevada Test Site and from the GNOME event in New Mexico, confirming a regional difference between eastern and western Pn velocities. Time residuals are also considered in relation to crustal structure under Lake Superior. Amplitudes of Pn and P and S or Lg are shown, and the variation of amplitude with charge is measured for Pn and P and S or Lg for the limits available. Some of the energy considerations related to coupling and signal transmission are discussed, and examples of signals are shown.

CONTENTS

TABLE

FIGURES

FIGURES, CONT.

FIGURES, CONT.

1. Introduction.

a. As of the present writing, three series of chemical explosions have been detonated on the bottom of Lake Superior in a joint research program referred to as the Lake Superior Seismic Experiment. This crustal-upper mantle research effort, carried out by a group of interested governmental and private organizations, is to be described in a volume now in the process of publication by the Carnegie Institution of Washington, and which is to include the material here reported. The present presentation, as an internal AFTAC/VSC technical report, includes only the long range data obtained from the van stations of the Long Range Seismic Measurements (LRSM) program and from five experimental observatories plus a few scattered deep-well installations, all operated as part of the VELA-UNIFORM program under the auspices of the Advanced Research Projects Agency of the Department of Defense, with technical direction by the Air Force Technical Applications Center (AFTAC).

b. The US Coast Guard, in association with the University of Wisconsin-Carnegie Institution of Washington supervisory group, detonated about eight 1-ton shots during July 1963. An additional series of about 40 shots was detonated during July 1964, monitored by the University of Wisconsin. This shot group, principally of 1-ton charges, included some weaker shots of 250, 500, and 1,000 pounds, and tested two types of chemical explosive being compared for efficiency. A third series of 10 shots was detonated in October 1964, under the supervision of the US Geological Survey, Crustal Studies Branch, as part of a

transcontinental measurements program. This shot group included two chemical charges each of 2,000, 4,000, 6,000, 12,000, and 20,000 pounds, one set of which was detonated at a common reference point in the western part of the lake, and the others at several adjacent points previously found to provide good signal strength at a distance.

c. A substantial portion of the shots of each series was recorded at various azimuths and up to distances of more than 2,500 km. The following report presents data on the principal phases recorded, their travel times, and amplitudes, and offers some comment on the travel paths, sub-Lake Superior structural implications, and some of the energy considerations involved.

2. Instrumentation.

a. Instrumentation at each of the LRSM mobile stations consists of 3-component short-period Benioff and 3-component Sprengnether long-period seismographs. Data are recorded on 35mm film and on 1-inch 14-channel magnetic tape. These stations are equipped to record WWV continuously in order to provide accurate time control. Calibration is accomplished at least once a day. Details of the instrumentation and operating procedures for these stations are given in "Routine Operating Instructions," obtainable from Geotech Division, Teledyne Industries, Inc., Dallas, Texas.

b. The five VELA observatories also have both long-period and short-period 3-component instrumentation in addition to their other specialized facilities. Each also maintains a continuously operating array, the

geometry and circuitry being somewhat variable between observatories and from one time period to another. In general, individual instrument traces, summations, and filtered summations are available for various seismometer groupings. Most of the array short-period vertical instruments are of the Johnson-Matheson type.

c. Several experimental deep-well short-period installations also received signals. In general, their system characteristics were similar to those of the surface Benioff instruments. Usually the well arrangement included a surface vertical instrument, and a shallow, and a deep vertical instrument, all with similar response characteristics.

d. All of the stations described are operated under the direction of AFTAC as part of the VELA-UNIFORM program, as noted in the introduction.

3. Data and Procedure.

a. Shot positions in Lake Superior are shown on the lake map of Figure 1, and the locations of the recording stations are shown on the United States map of Figure 2. Figure 3 is a chart showing the distribution of signals received from the first or principal shot series, as an example of the coverage obtainable using 1-ton shots at the average magnifications shown.

b. Analysis for this report was restricted to the film recordings, and, since no long-period signals were detected, the emphasis was on the short-period vertical instruments. The horizontal-instrument records were also used where S (or Lg) phase motion was detectable.

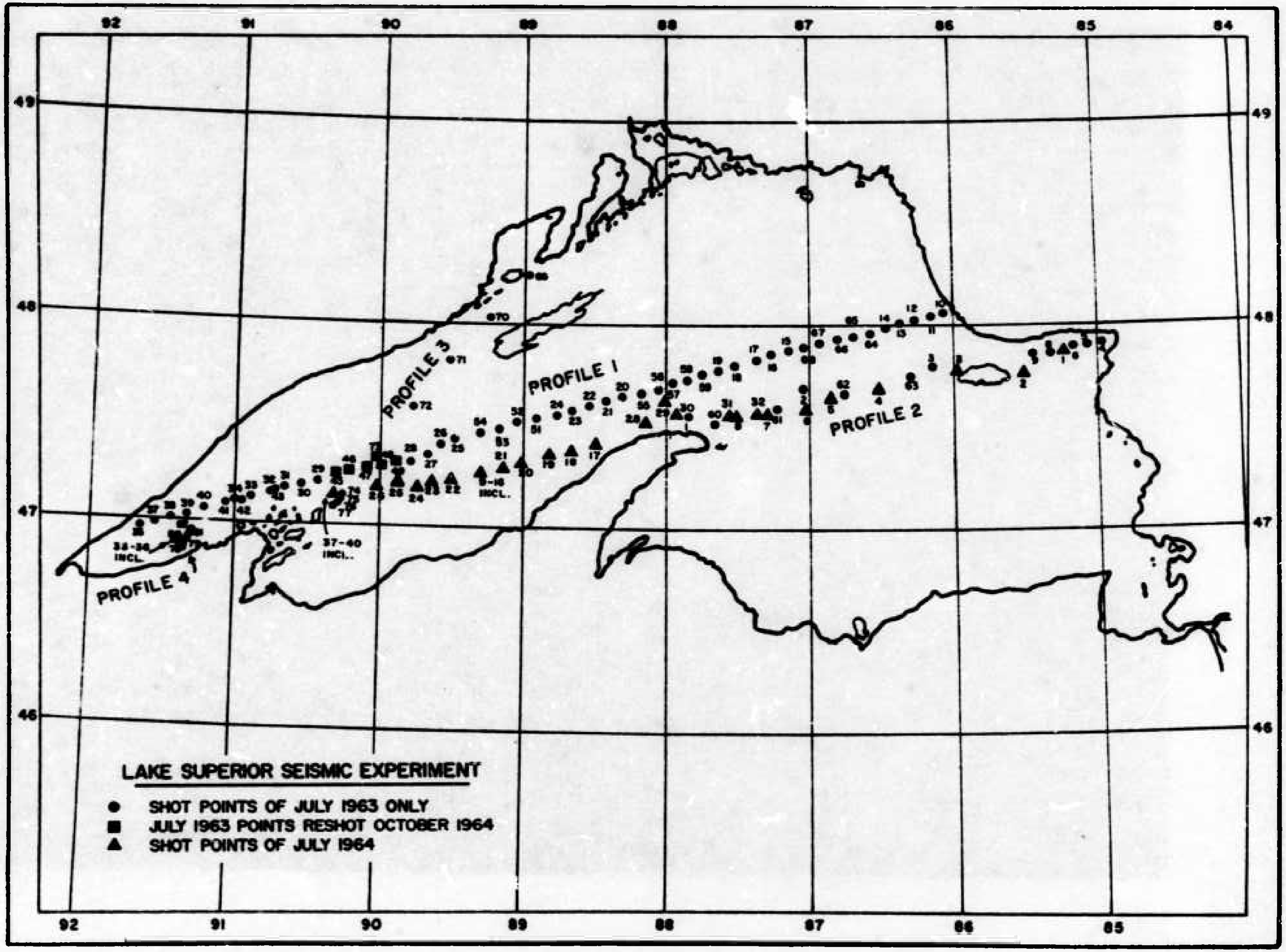


Figure 1
AFTAC/VSC

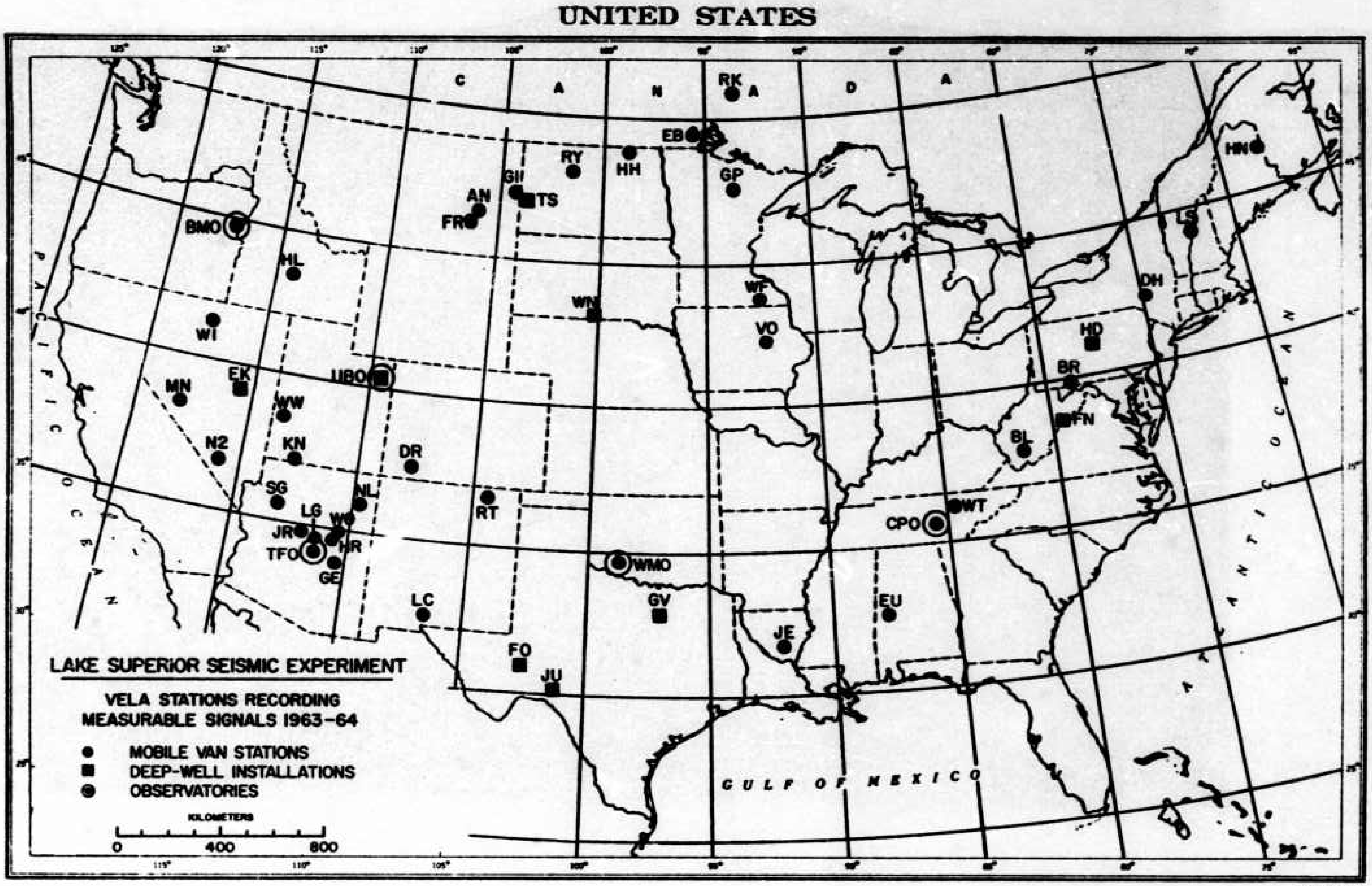
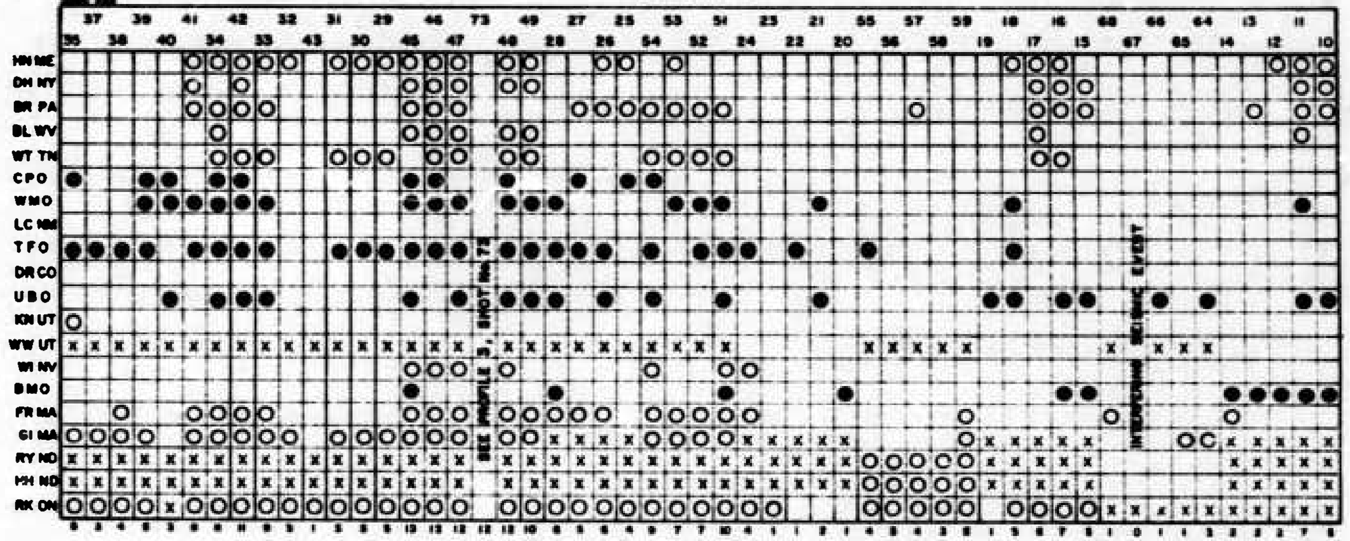
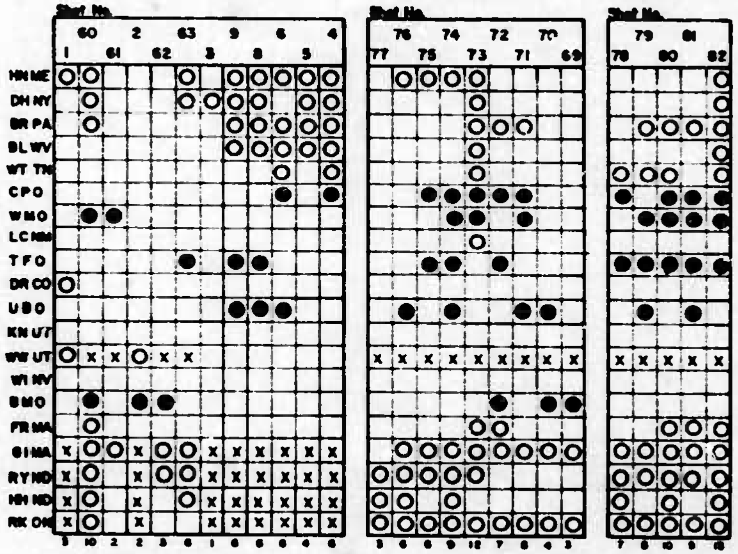


Figure 2
AFTAC/VSC





Station	TOTAL % OF 78 SHOTS MEASURABLE	% OF SHOTS OPERATIONAL	AVERAGE GAIN AT X10 FOR SP-Z SINGLE	SUM	FILTERED SUM
HN ME	45 %	100 %	132 K		
DH NY	27	100	45		
BR PA	44	100	205		
BL WV	19	100	50		
WT TN	29	100	145		
CPO	28	100	420		
WMO	35	100	500		
LC NM	01	100	355		
TFO	47	100	600	(6500)K	(650)K
DR CO	01	100	385		
UBO	38	100	600	(2000)K	
KN UT	01	100	345		
WW UT	03	29	475		
WI NV	09	100	405		
BMO	22	100	—	(2000)K	(5000)K
FR MA	35	100	110		
GI MA	52	66	115		
RY ND	23	36	20		
MH ND	17	36	20		
RK ON	67	76	195		

O MOBILE STATION ● OBSERVATORY X INOPERATIVE ON SP-Z

SUMMARY OF MEASURABLE SIGNALS JULY 1963

LAKE SUPERIOR SEISMIC EXPERIMENT

Figure 3
AFTAC/VSC

c. The Seismic Data Laboratory[1] digital computer was utilized to provide all required shot-to-station distances, as well as the azimuths shot-to-station and station-to-shot. Predicted arrival times were computed for all signals at all stations, using the Jeffreys-Bullen (J-B) surface travel-time curve. This facilitated record reading and phase identification.

d. Usually the first arrivals for the most distant stations were not easily identifiable above the existing noise background, and so it was fortunate that most of the signals appeared in multiple-trace presentations. At the observatories, the signal alignments were from different single-instrument traces or summations from the array in question. For the mobile stations, a similar signal alignment usually resulted from successive shots at one or more even hourly intervals for the same instrument, the recording rate of one trace-revolution per hour bringing the signals to the same film area for a succession of several shots fired the same Greenwich (Z) day.

4. Analysis and Discussion. Information from the stations described above, which were in routine operation during some time interval within the 1963-64 shot series, is considered in the following under several specific headings:

a. Travel Times.

(1) For the July 1963 explosion program, a composite

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[1] Operated by the Earth Sciences Division, Teledyne Industries, Inc., under AFTAC direction.

first-arrival tabulation has already been published[1] listing the details of all shot locations and times and the positions of all recording stations that detected measurable signals. Location data for the five VELA observatories and the LRSM mobile stations of interest were included with similar information from other participating groups. The published travel times were also made available on punch cards; and printouts by shot, by distance, and by station are on file.

(2) Travel-time data from the two 10-ton shots of the October 1964 series have also had some informal distribution to government agencies and other organizations and are shown here as a sample presentation (Table I).

(3) These data, including only first arrivals, plus similar data for the remaining shots of July and October 1964, when added to secondary and later arrival data and supplemented with numerous amplitude measurements, comprise a mass of information too large to list here in detail. It is hoped that the following graphs will show the principal features of interest, beginning with the travel times.

(4) For the July 1963 shots, Figure 4 displays the first-arrival residuals with reference to a constant velocity of 8.1 km/sec and includes the J-B surface curve for reference. These data have been separated into five regional geographical zones related to general tectonic structure. It will be seen that signals were received several seconds earlier than J-B arrivals in the three eastern zones and that they

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[1] "Lake Superior Seismic Experiment: Shots and Travel Times," by Dr. John S. Steinhart. Journal of Geophysical Research, Vol 69, No. 24, Dec 15, 1964, p 5335.

Pn and P ARRIVAL TIMES
10 TON CHEMICAL SHOTS
LAKE SUPERIOR, OCT 1964

SHOT 49A — DAY 10, MON 10, YEAR 64, HR 8, MIN 30, SEC 00.3Z, LATITUDE 47.373N, LONGITUDE 89.883W

VELA STATION	CODE	LATITUDE	LONGITUDE	DISTANCE DEGREES	DISTANCE KM	AZIMUTH EPI-STA	AZIMUTH STA-EPI	ARRIVAL TIME	TRAVEL TIME	C or R	GRADE	OBS-J.B.
GRAND RAPIDS, MN	GP MN	47.664N	93.489W	2.462	274	278.1	95.5	08 30 41.0Z	om 40.75	C	F	-1.4
WYKOFF, MINN	WF MN	43.801N	92.373W	3.976	442	207.0	25.2	08 31 02.9Z	1 02.6	x	G	-1.0
RED LAKE, ONT	RK ON	50.839N	93.672W	4.269	475	325.7	142.9	08 31 06.4Z	1 06.1	C	G	-1.7
VINTON, IOWA	VO IO	42.225N	92.127W	5.389	599	198.0	16.5	08 31 22.0Z	1 21.7	C	G	-1.9
RYDER, N. DAK	RY ND	48.097N	101.494W	7.864	875	279.6	91.0	08 31 55.3Z	1 55.0	x	G	-3.4
BERLIN, PA	BR PA	39.924N	78.845W	10.919	1214	129.0	316.6	08 32 35.9Z	2 35.6	C	G	-5.0
BECKLEY, W. VA	BL WV	37.799N	81.310W	11.458	1274	143.5	329.3	08 32 42.1Z	2 41.8	C	G	-6.2
DELHI, N. Y.	DH NY	42.244N	74.388W	11.816	1314	110.2	300.8	08 32 47.4Z	2 47.1	C	G	-5.7
CPSO, TENN	CPO 8	35.595N	85.570W	12.201	1357	163.1	346.0	08 32 52.7Z	2 52.4	x	G	-5.6
LISBON, N. H.	LS NH	44.238N	71.922W	12.917	1436	97.5	290.3	08 33 02.9Z	3 02.6	x	G	-4.9
WMSO, OKLA	WMO 6	34.718N	98.589W	14.233	1583	210.5	24.7	08 33 18.0Z	3 17.7	x	G	-7.3
HOULTON, ME	HN ME	46.162N	67.986W	15.052	1674	86.5	282.5	08 33 29.4Z	3 29.1	x	G	-6.5
RATON, N. M.	RT NM	36.729N	104.360W	15.098	1679	230.5	40.7	08 33 32.6Z	3 32.3	x	F	-4.2
GRAPEVINE, TEX	GV TX	32.886N	96.998W	15.448	1718	203.0	18.4	08 33 35.9Z	3 35.6	x	VP	-5.2
JENA, LA	JE LA	31.785N	92.015W	15.653	1741	186.7	5.4	08 33 41.1Z	3 40.8	C	G	-2.7
UBSO, UTAH	UBO 10	40.322N	109.569W	15.832	1760	250.7	57.1	08 33 41.5Z	3 41.2	x	P	-4.8
SCHEFFERVILLE, QB	SV2QB	54.815N	66.759W	16.272	1809	54.2	252.3	08 33 46.3Z	3 46.0	x	G	-5.4
DURANGO, COLO	DR CO	37.465N	107.783W	16.479	1832	239.6	47.4	08 33 50.8Z	3 50.5	x	F	-3.9
HAILEY, IDAHO	HL2ID	43.561N	114.419W	17.604	1958	266.5	69.0	08 34 06.4Z	4 06.1	x	G	-2.3
NAZLINI, ARIZ	NL AZ	35.901N	109.569W	18.594	2068	239.1	45.9	08 34 19.9Z	4 19.6	x	F	-1.1
BMSO, OREGON	BMO 3	44.849N	117.306W	19.144	2129	272.5	72.7	08 34 23.8Z	4 23.5	x	G	-3.7
LAS CRUCES, N.M.	LC NM	32.402N	106.599W	19.637	2184	226.4	35.6	08 34 31.2Z	4 30.9	x	G	-2.1
KANAB, UTAH	KN UT	37.023N	112.828W	19.829	2205	246.9	51.4	08 34 34.7Z	4 34.4	x	F	-0.8
WINSLOW, ARIZ	WO AZ	34.881N	110.621W	19.921	2215	238.7	44.9	08 34 35.4Z	4 35.1	x	F	-1.2
HEBER, ARIZ	HR AZ	34.670N	110.766W	20.155	2241	238.5	44.7	08 34 36.0*Z	4 35.7	C	G	-3.2
EUREKA, NEV	EK NV	39.209N	115.710W	20.426	2271	255.9	58.0	08 34 40.7Z	4 40.4	C	G	-1.3
GLOBE, ARIZ	GE AZ	33.776N	110.528W	20.663	2298	236.3	42.8	08 34 42.6Z	4 42.3	x	F	-1.8
TFSO, ARIZ	TFO 1	34.268N	111.270W	20.733	2305	238.6	44.4	08 34 43.8Z	4 43.5	x	G	-1.3
JEROME, ARIZ	JR AZ	34.826N	111.990W	20.764	2309	240.9	46.2	08 34 44.4Z	4 44.1	x	F	-1.0
LONG VALLEY, AZ	LG AZ	34.408N	111.546W	20.794	2312	239.3	45.0	08 34 45.3Z	4 45.0	C	G	-0.5
SELIGMAN, AZ	SG AZ	35.641N	113.261W	20.982	2333	244.5	48.9	08 34 47.2Z	4 46.9	x	F	-0.5
SNOWFLAKE, AZ	SN AZ	33.864N	111.693W	21.266	2365	238.5	44.1	08 34 49.4Z	4 49.1	x	G	-1.1
TEST SITE, NEV	N2 NV	36.633N	115.983W	22.066	2454	250.4	52.8	08 34 59.5Z	4 59.2	x	F	+1.1
MINA NEV	MN NV	38.436N	118.148W	22.448	2496	256.9	57.5	08 35 02.0Z	5 01.7	x	F	-0.4
LINEAR ARRAY	TFO 74	34.325N	111.233W	20.670	2298.4	238.6	44.5	08 34 43.2Z	4 42.9	x	G	-1.3
TFSO, ARIZ	TFO 21	34.287N	111.268W	20.718	2303.7	238.6	44.5	08 34 43.8Z	4 43.5	x	G	-1.2
(KEY POINTS)	TFO 63	34.248N	111.302W	20.765	2308.9	238.6	44.4	08 34 44.4Z	4 44.1	x	G	-1.1

SHOT 45E — DAY 10, MON 10, YEAR 64, HR 11, MIN 30, SEC 00.3Z, LATITUDE 47.312N, LONGITUDE 90.300W

VELA STATION	CODE	DISTANCE DEGREES	DISTANCE KM	AZIMUTH EPI-STA	AZIMUTH STA-EPI	ARRIVAL TIME	TRAVEL TIME	C or R	GRADE	OBS-J.B.	REMARKS
GRAND RAPIDS, MN	GP MN	2.192	244	280.4	98.1	11 30 37.4Z	0 37.1	x	F	-1.1	
WYKOFF, MINN	WF MN	3.801	423	203.3	21.8	11 31 00.4Z	1 00.1	C	G	-1.0	
RED LAKE, ONT	RK ON	4.168	464	329.1	146.6	11 31 05.0Z	1 04.7	C	G	-1.6	
VINTON, IOWA	VO IO	5.250	584	195.0	13.7	11 31 19.7Z	1 19.4	C	G	-2.2	
RYDER, N. DAK	RY ND	7.596	845	280.0	91.8	11 31 52.0Z	1 51.7	x	G	-3.0	
BERLIN, PA	BR PA	11.103	1235	127.5	315.4	11 32 38.4Z	2 38.1	C	G	-5.1	
BECKLEY, W. VA	BL WV	11.580	1288	141.9	328.0	11 32 42.7Z	2 42.4	C	G	-7.2	
DELHI, N. Y.	DH NY	12.062	1341	109.2	300.1	11 32 50.8Z	2 50.5	C	G	-5.6	
CPSO, TENN	CPO 8	12.228	1360	161.5	344.6	11 32 52.6Z	2 52.3	x	G	-6.1	Vault
LISBON, N. H.	LS NH	13.191	1467	96.7	289.9	11 33 06.1Z	3 05.8	x	P	-5.4	
WMSO, OKLA	WMO 6	14.039	1561	209.3	23.9	11 33 14.9Z	3 14.6	x	G	-7.8	Vault
HOULTON, ME	HN ME	15.338	1706	86.1	282.4	11 33 32.6Z	3 32.3	x	G	-7.0	
RATON, N. M.	RT NM	14.842	1650	229.6	40.2	11 33 28.8Z	3 28.5	x	F	-4.7	
GRAPEVINE, TEX	GV TX	15.283	1699	201.9	17.5	-	-	-	-	-	
JENA, LA	JE LA	15.563	1731	185.5	4.4	11 33 39.8Z	3 39.5	x	F	-2.8	
UBSO, UTAH	UBO 10	15.544	1728	250.3	56.9	11 33 39.0Z	3 38.7	x	P	-3.6	Vault
SCHEFFERVILLE, QB	SV2QB	16.538	1839	54.3	252.7	11 33 47.0Z	3 46.7	x	F	-8.0	Z1
DURANGO, COLO	DR CO	16.205	1802	238.9	47.1	11 33 47.2Z	3 46.9	x	P	-4.0	
HAILEY, IDAHO	HL2ID	17.318	1926	266.4	69.1	11 34 02.7Z	4 02.4	x	P	-2.4	
NAZLINI, ARIZ	NL AZ	18.320	2037	238.5	45.6	11 34 17.6Z	4 17.3	x	VP	0	
BMSO, OREGON	BMO 3	18.864	2098	272.5	72.9	11 34 22.4Z	4 22.1	x	VP	-1.8	Vault
LAS CRUCES, N.M.	LC NM	19.391	2156	225.7	35.1	11 34 28.4Z	4 28.1	x	G	-2.1	
KANAB, UTAH	KN UT	19.545	2173	246.4	51.2	11 34 31.5Z	4 31.2	x	VP	-0.7	
WINSLOW, ARIZ	WO AZ	19.647	2185	238.1	44.7	-	-	-	-	-	
HEBER, ARIZ	HR AZ	19.882	2211	237.9	44.4	11 34 34.2Z	4 33.9	x	F	-2.0	*or 37.0 or 37.7
EUREKA, NEV	EK NV	20.136	2239	255.6	58.0	11 34 37.7Z	4 37.4	x	G	-1.3	
GLOBE, ARIZ	GE AZ	20.394	2268	235.7	42.5	11 34 39.9Z	4 39.6	x	VP	-1.7	
TFSO, ARIZ	TFO 1	20.459	2275	238.0	44.2	11 34 41.3Z	4 41.0	x	P	-1.0	Vault, Z1
JEROME, ARIZ	JR AZ	20.487	2278	240.3	45.9	-	-	-	-	-	
LONG VALLEY, AZ	LG AZ	20.519	2282	238.7	44.7	11 34 42.6	4 42.3	x	P	-0.3	
SELIGMAN, AZ	SG AZ	20.700	2302	244.0	48.7	11 34 46.0	4 45.7	x	VP	+1.2	
SNOWFLAKE, AZ	SN AZ	20.993	2334	237.9	43.9	11 34 47.2	4 46.9	x	F	-0.5	
TEST SITE, NEV	N2 NV	21.778	2422	250.0	52.6	-	-	-	-	-	from playout
MINA NEV	MN NV	22.159	2464	256.6	57.4	11 34 58.5	4 58.2	x	P	-1.0	
LINEAR ARRAY	TFO 74	20.397	2268.1	238.0	44.2	11 34 40.7	4 40.4	x	F	-1.0	Linear Array NE
TFSO, ARIZ	TFO 21	20.444	2273.3	238.0	44.2	11 34 41.2	4 40.9	x	F	-0.9	" " Center
(KEY POINTS)	TFO 63	20.492	2278.6	238.0	44.2	11 34 41.9	4 41.6	x	F	-0.7	" " SW

TABLE I. VELA STATION DATA

03 MAR 65
AFTAC/VSC

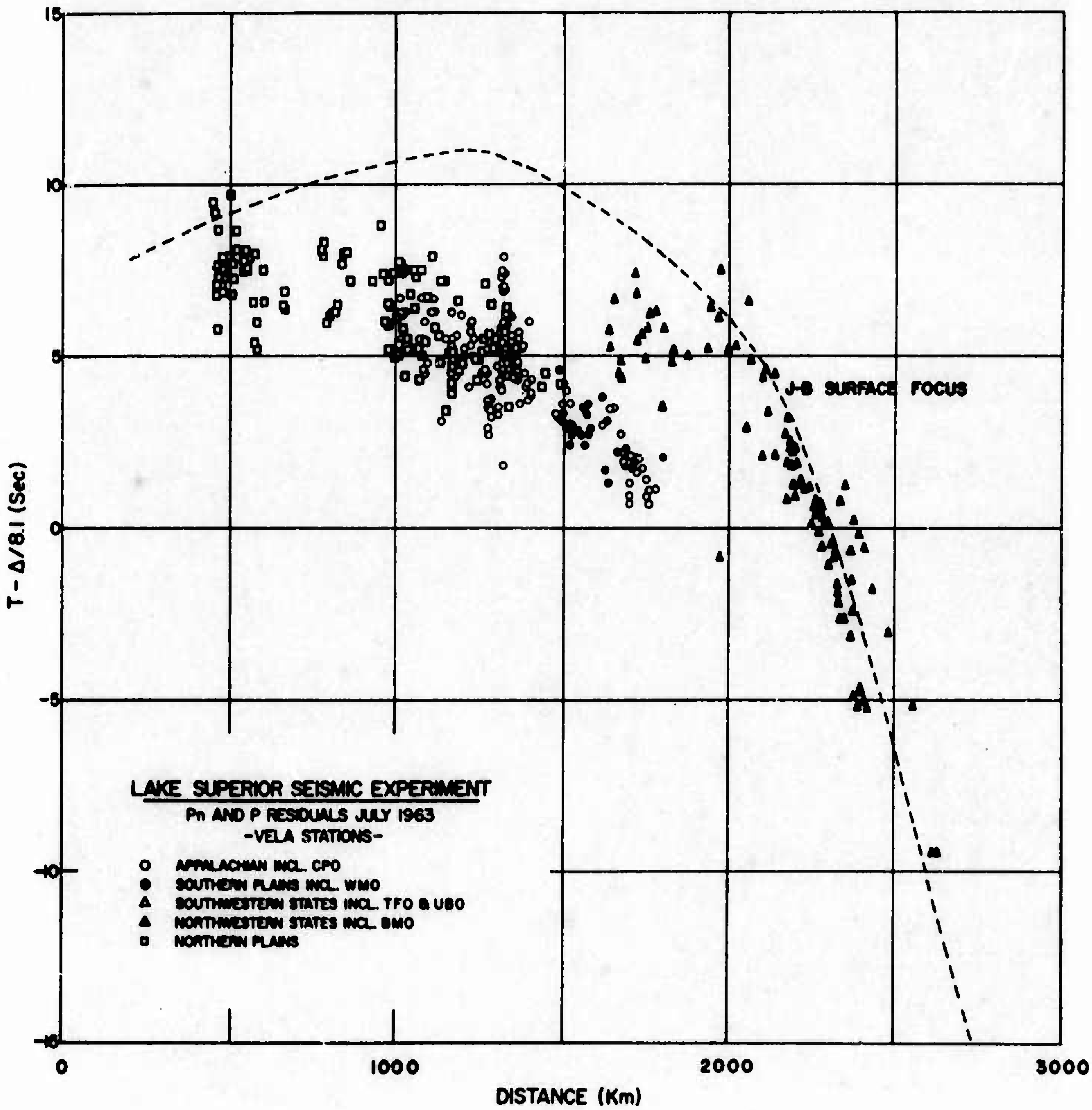

Figure 4
AFTAC/VSC

reverted to a J-B distribution in the northwestern and southwestern zones where at least a part of the path lies west of the Rocky Mountain front. Data from the July and October 1964 shot series are very similar and add statistical support to the distribution shown in Figure 4.

(5) This graph may be contrasted with Figure 5, which is a similar plot for 10 nuclear events detonated underground at the Nevada Test Site. This group of data is more evenly distributed about the J-B curve, though again the signals received in the northern plains tend to be somewhat early.

(6) Figures 4 and 5 may also be compared with Figure 6, which is a reproduction of the corresponding plot for the GNOME (New Mexico) nuclear event, as taken from a published report by Dr. Romney, et al[1].

(7) These three figures indicate a distinct difference between eastern and western travel-time paths. It may also be noted that the differences cease at 2,200 or 2,300 km from the source, suggesting that beyond this distance penetration to a deeper and more uniform travel path has occurred.

(8) The Lake Superior graph, Figure 4, is similar to the eastern section of the GNOME graph, Figure 6, as well as to graphs from SS VILLAGE[2] and SALMON[3] and generally for earthquakes in the eastern United States.

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[1] "Travel Times and Amplitudes of Principal Body Phases Recorded from GNOME," Romney, et al, Bulletin of the Seismological Society of America, Vol 52, No. 5, p 1064.

[2] "Long Range Seismic Measurements, Project 8.4, Seismic Waves from the SS VILLAGE Explosion," Seismic Data Laboratory Report No. 112, Earth Sciences Division, United ElectroDynamics, Inc., 23 November 1964, Figure 3.

[3] "Long Range Seismic Measurements, Project 8.4, SALMON," Seismic Data Laboratory Report No. 113, Earth Sciences Division, Teledyne Systems Company, 7 December 1964, Figure 3, p 11. (Teledyne Systems Company taking over United ElectroDynamics, Inc., at about this date)

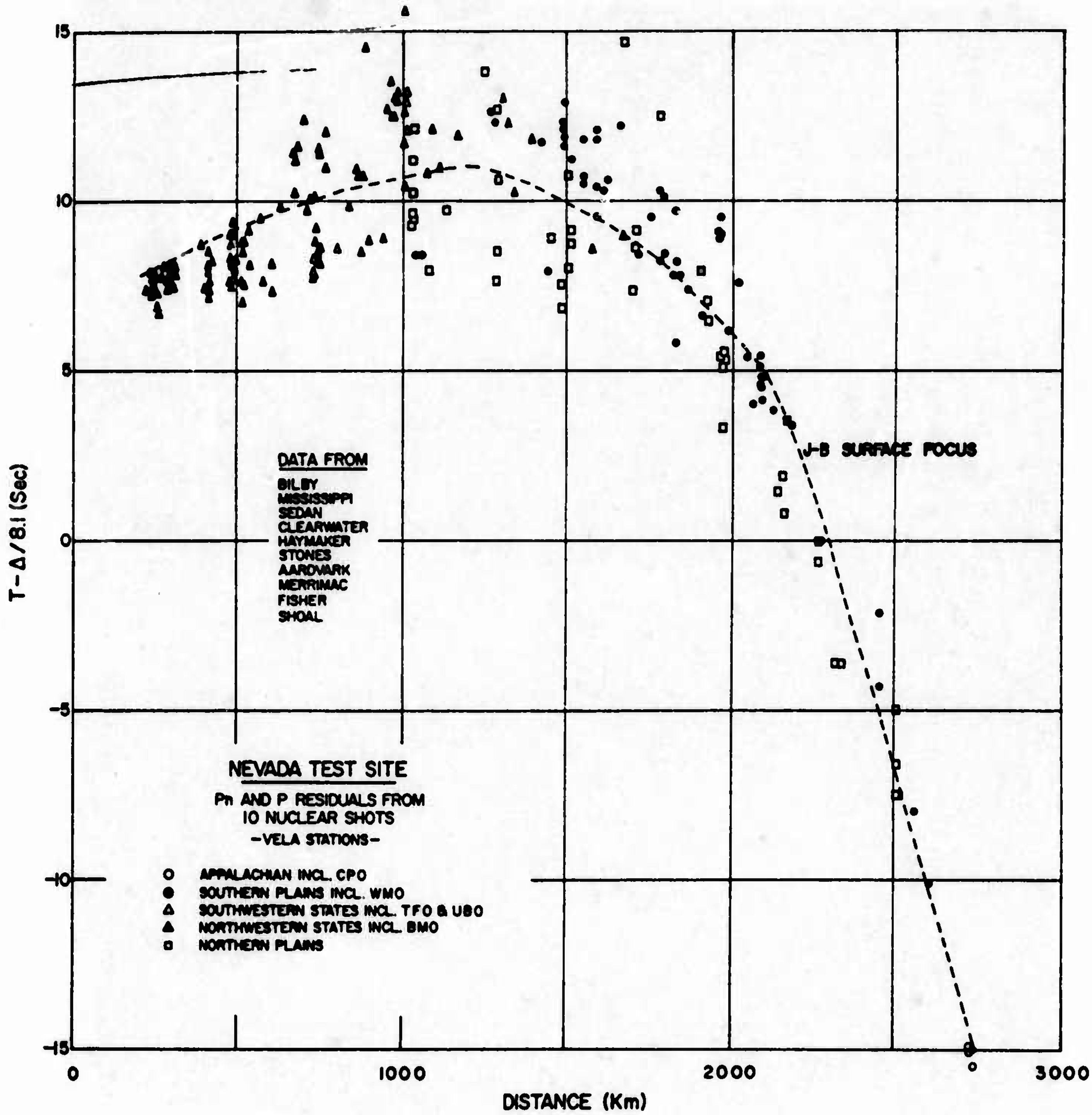

Figure 5
AFTAC/VSC

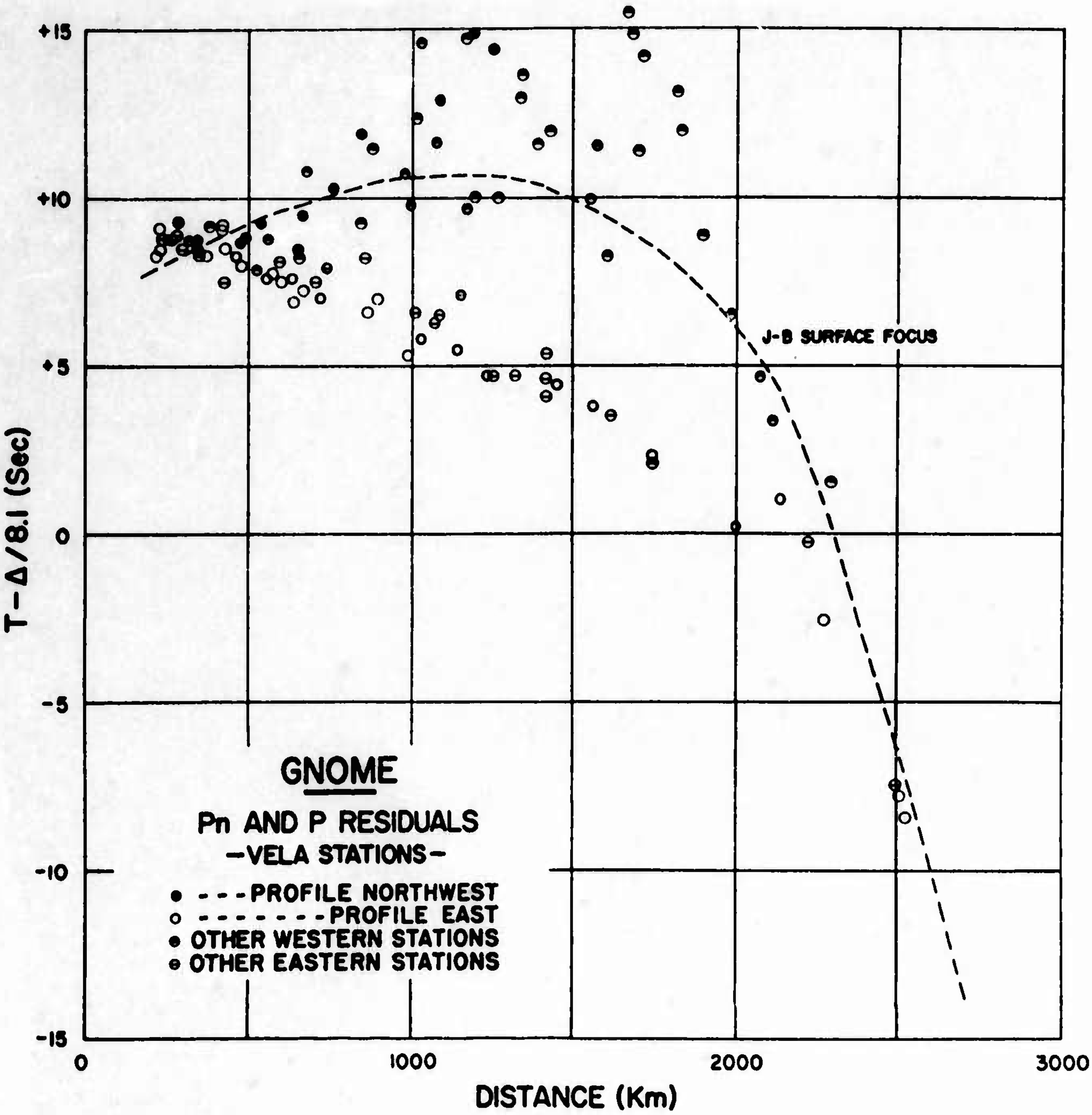

Figure 6
AFTAC/VSC

An average Pn velocity of about 8.4 km/sec is thus suitable for use in the eastern United States and one of about 7.9 km/sec in the western United States.

(9) For individual stations, the variations in travel time from shot points in different parts of Lake Superior could theoretically be utilized to work out details of crustal structure under the lake. Data from other organizations[1] have suggested a possible crustal anomaly under the center of the lake north of the Keweenaw Peninsula. An attempt was made to treat this situation as a 2-layer problem using shot point profiles recorded at more than a dozen stations. Starting with single stations nearly in line with the shot profiles crossing the lake, time profiles were made in terms of residuals from the J-B surface curve. Unfortunately only the profiles based on data from the Tonto Forest Seismological Observatory, Arizona (TFO), and from the Uinta Basin Seismological Observatory, Utah (UBO), showed time differences adequate to suggest a structural anomaly of any size. The best of these, that from TFO (Figure 7), indicates a possible change in average residual of at least 2 seconds somewhere between shot points 27 and 52. By coincidence, this break at shot point 27 is just 2,300 km from TFO, so that there is no assurance that time paths from the western end of the lake can be compared directly with those from the eastern end, if the change of paths suggested at 2,300 km in Figure 4 is borne in mind. Another

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[1] For example: "An Interpretation of the Lake Superior Experiment First-Arrival Data by the Time Term Method," M. J. Berry and G. F. West, Inst. of Earth Sciences, University of Toronto, Bulletin of the Seismological Society of America, Vol 56, No. 1, p 141.

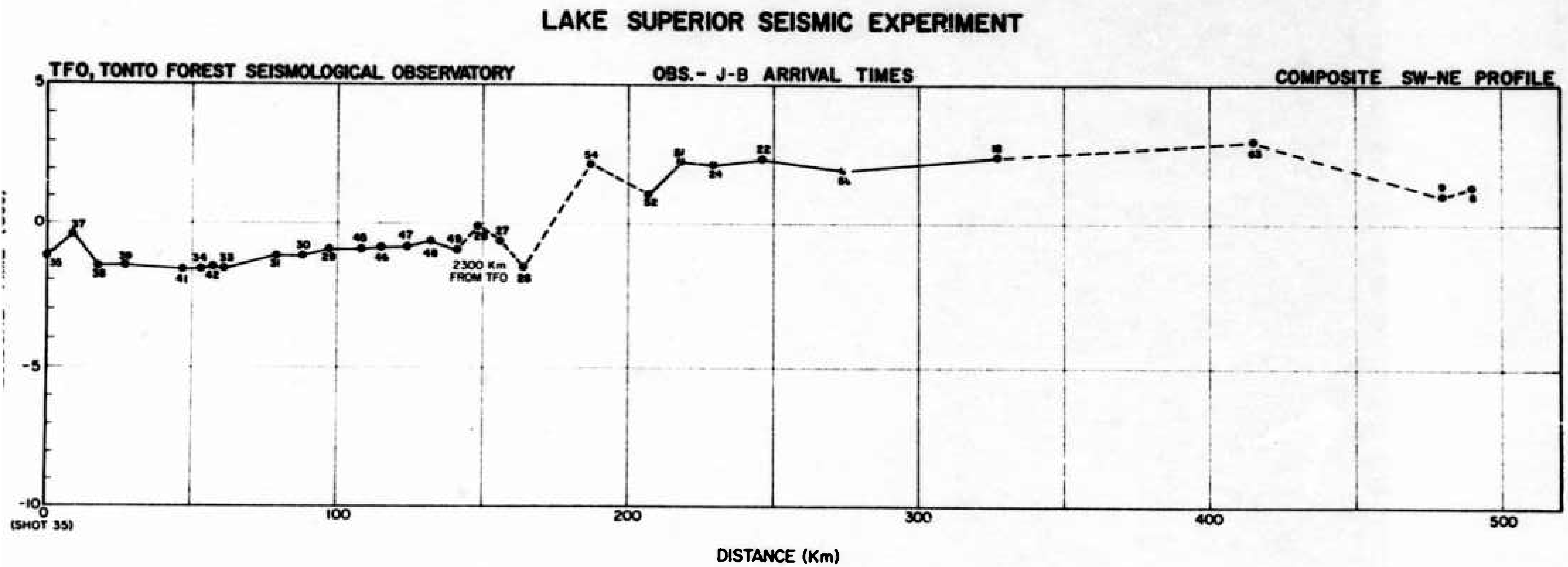
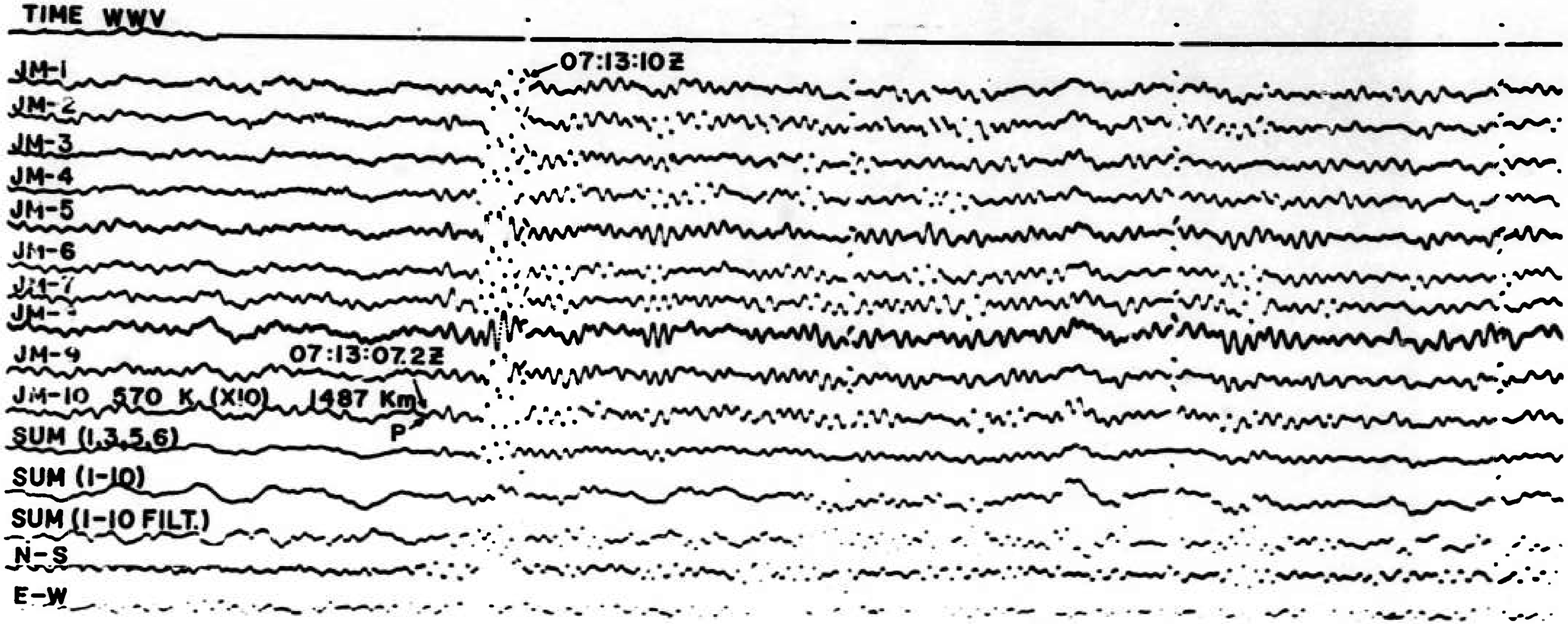


Figure 7
AFTAC/VSC

difficulty with the profile of Figure 7 is that signals from the western end of the lake were in general somewhat stronger than those from the eastern end, so that the identifiable first motion may not be the same phase for the eastern and western shot points. In view of these complications, it is suggested that the data presented here may be more useful in checking structures postulated from other data than in providing structural indications directly. It may further be noted in Figure 7 that only six good readings for the eastern end of the lake showed delayed arrivals as measured from the July 1963 shot series. None of the shots from the July or October 1964 programs add anything to the profile as shown.

(10) In addition to the Pn and P arrivals so far mentioned, some indications of other phases were noted. One of these is illustrated in Figure 8, which shows a recording at the Wichita Mountains Seismological Observatory, Oklahoma (WMO), where a weak P arrival is followed about 2 seconds later by a stronger emergent phase. Evidences of multiple arrivals of this type make it doubtful that some of the weaker P arrivals represent true first motion. Another type of phase may be present in Figures 9 and 10, which are recordings at Red Lake, Ontario, and Glendive, Montana. Although these stations are at distances of 475 km and 980 km from the shot points in the same area of the lake, an emergent phase is seen in each recording at about 11 seconds after the first P arrival. It may be that the emergent phases represent SPS paths or something similar.



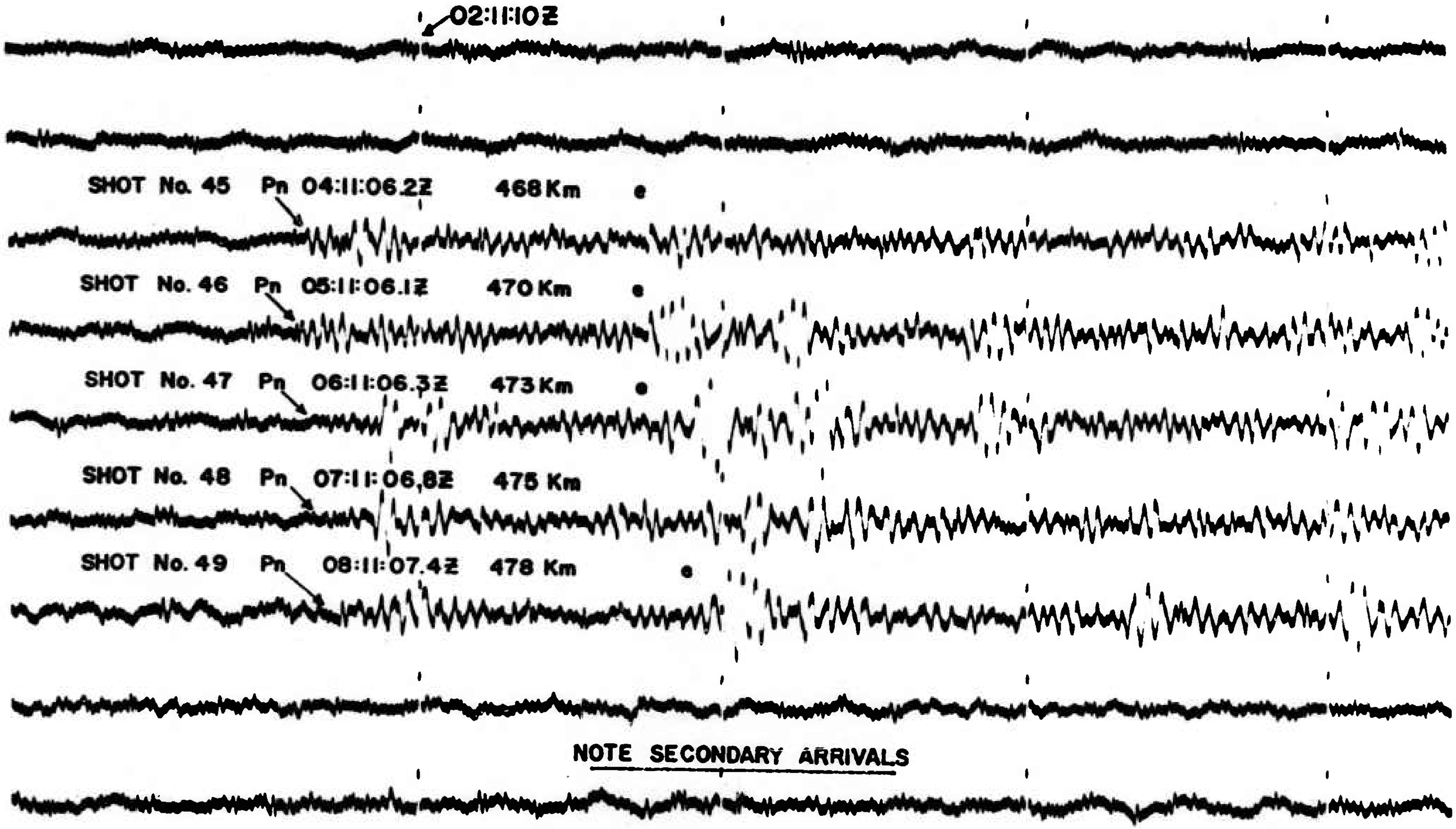
LAKE SUPERIOR SEISMIC EXPERIMENT

SHOT No. 81 30 JULY 63

P ARRIVAL

WMO WICHITA MOUNTAINS SEISMOLOGICAL OBSERVATORY, OKLAHOMA

Figure 8
AFTAC/VSC



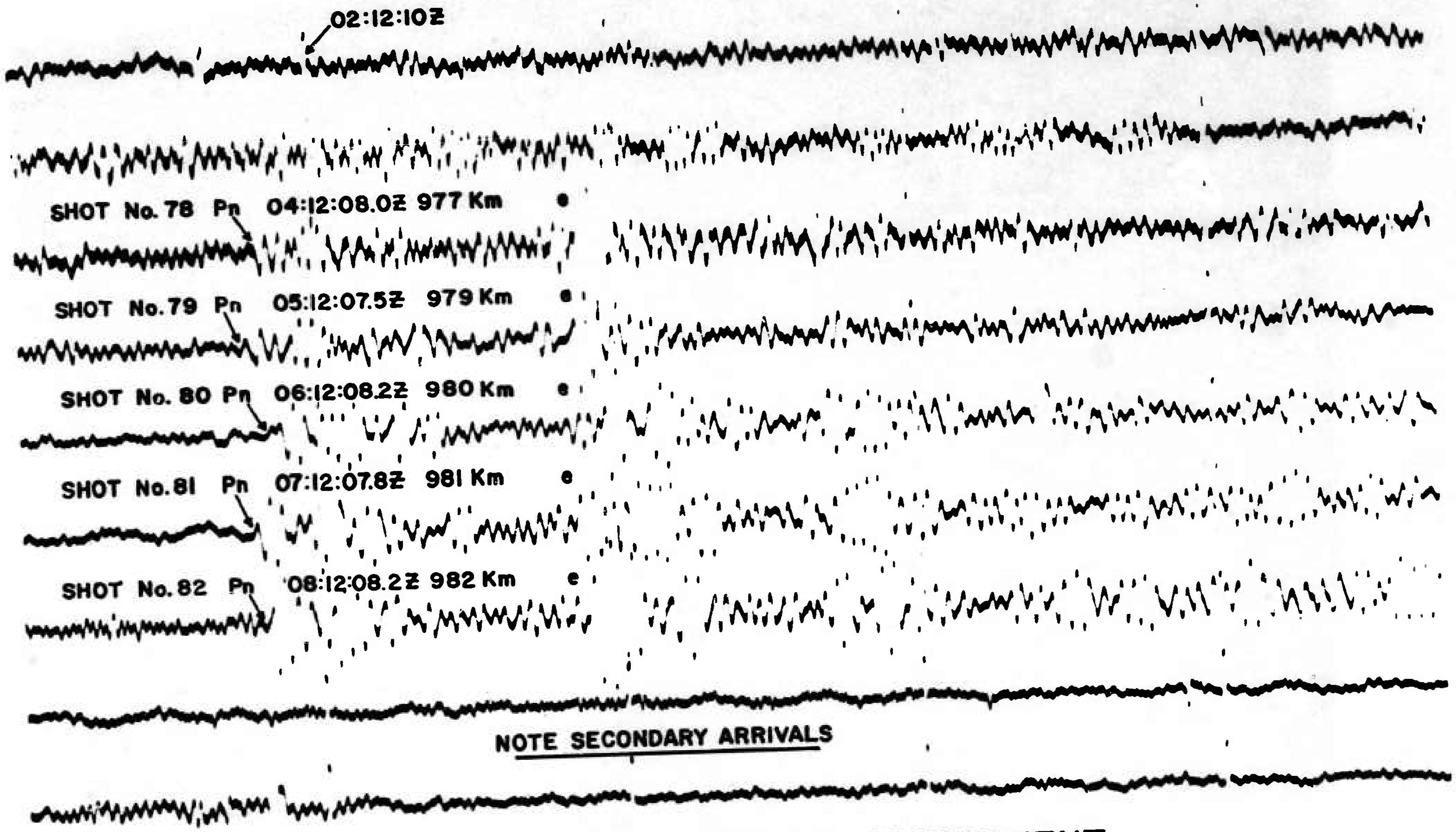
LAKE SUPERIOR SEISMIC EXPERIMENT

SHOTS OF 17 JULY 63

S-P VERTICAL—165.0 K (X10)

RK ON RED LAKE, ONTARIO

Figure 9
AFTAC/VSC



LAKE SUPERIOR SEISMIC EXPERIMENT

SHOTS OF 30 JULY 63

S-P VERTICAL — 120.3 K (X10)

GI MA GLENDIVE, MONTANA

Figure 10
AFTAC/VSC

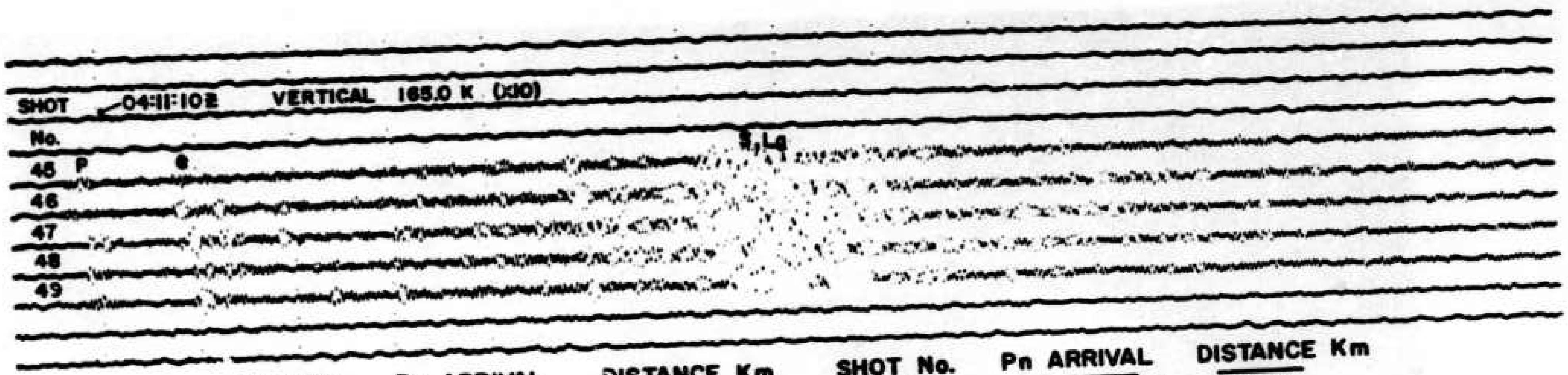
(11) Other phase arrivals recorded include S and Lg as indicated by arrival times and component of motion. Examples of these are shown in Figures 11 and 12, again recorded at Red Lake, Ontario, and Glendive, Montana. Figure 13 shows travel time versus distance in kilometers for S and Lg phases recorded from the July and October 1964 shot series. It will be seen that the points tend to lie along the J-B surface S curve, or along the 3.5 km/sec Lg arrival curve.

b. Amplitudes of Pn and P.

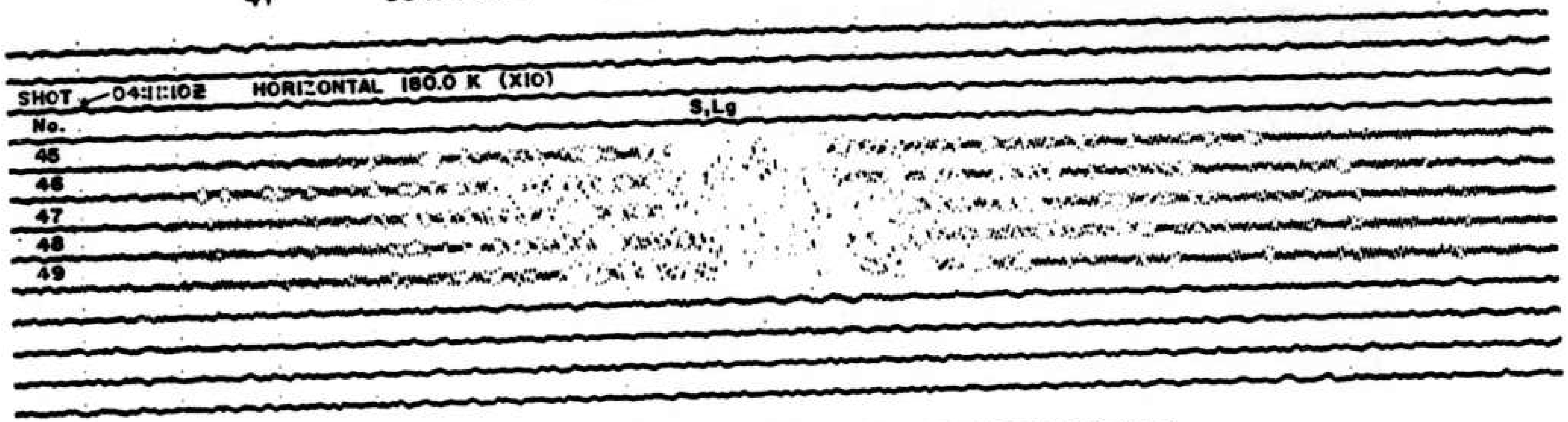
(1) Figure 14 is a graph of the amplitudes of Pn and P for the two 10-ton shots of 10 October 1964. These were the strongest shots detonated in any of the three series, and the effects noted are representative of those shown by a large number of readings from many weaker explosions.

(2) Amplitudes in the usual Pn range of approximately 200-1,200 km evidently do not fit an inverse cube rate of decrease, and it is doubtful that any other simple gradient will apply. Stations in the 400-600 km range including Wykoff, Minnesota (WF MN), Red Lake, Ontario (RK ON), and Vinton, Iowa (VO IO), appear relatively low. In the 800-1,300 km range, Ryder, North Dakota (RY ND), and Delhi, New York (DH NY), are on the high side; and other shots suggest that Winner, South Dakota (WN SD), would also be part of this high amplitude group.

(3) It seems unlikely that this amount by which these stations are high or low can be entirely explained in terms of regional amplitude levels, even if it is often noted that WN SD records abnormally high signals (in rather high noise). Thus there remains the possibility that



SHOT No.	Pn ARRIVAL	DISTANCE Km
45	04:11:06.2Z	468.0
46	05:11:06.1Z	470.1
47	06:11:06.3Z	472.6
48	07:11:06.8Z	475.3
49	08:11:07.4Z	478.0



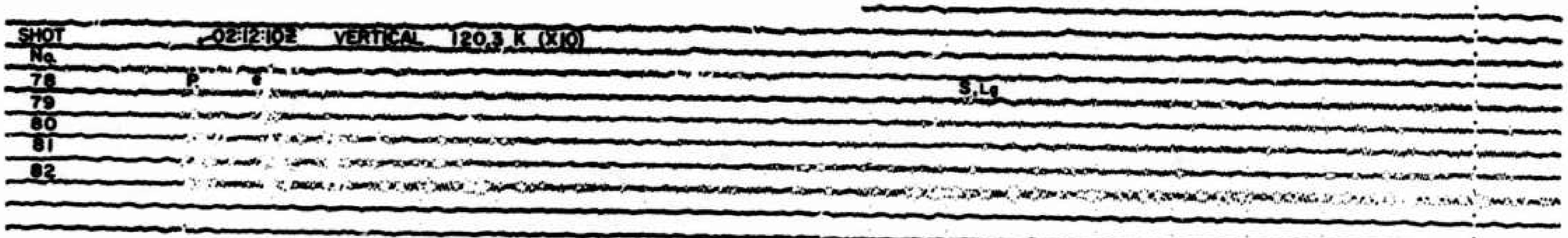
LAKE SUPERIOR SEISMIC EXPERIMENT

SHOTS OF 21 JULY 63

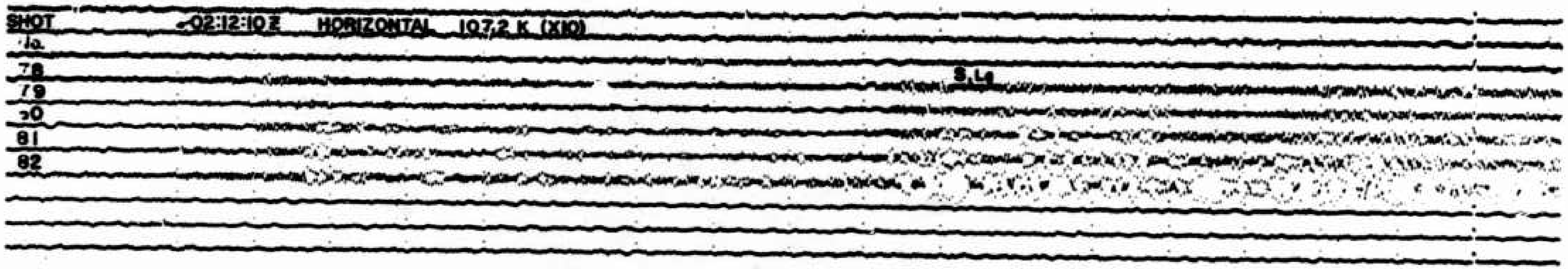
S & Lg MOTION ON SP VERTICAL AND SP HORIZONTAL (RADIAL)

RK ON RED LAKE, ONTARIO

Figure 11
AFTAC/VSC



SHOT No.	Pn ARRIVAL	DISTANCE Km	SHOT No.	Pn ARRIVAL	DISTANCE Km
78	04:12:08.0Z	977.0	81	07:12:07.6Z	981.0
79	05:12:07.5Z	979.0	82	08:12:08.2Z	982.0
80	06:12:08.2Z	980.0			



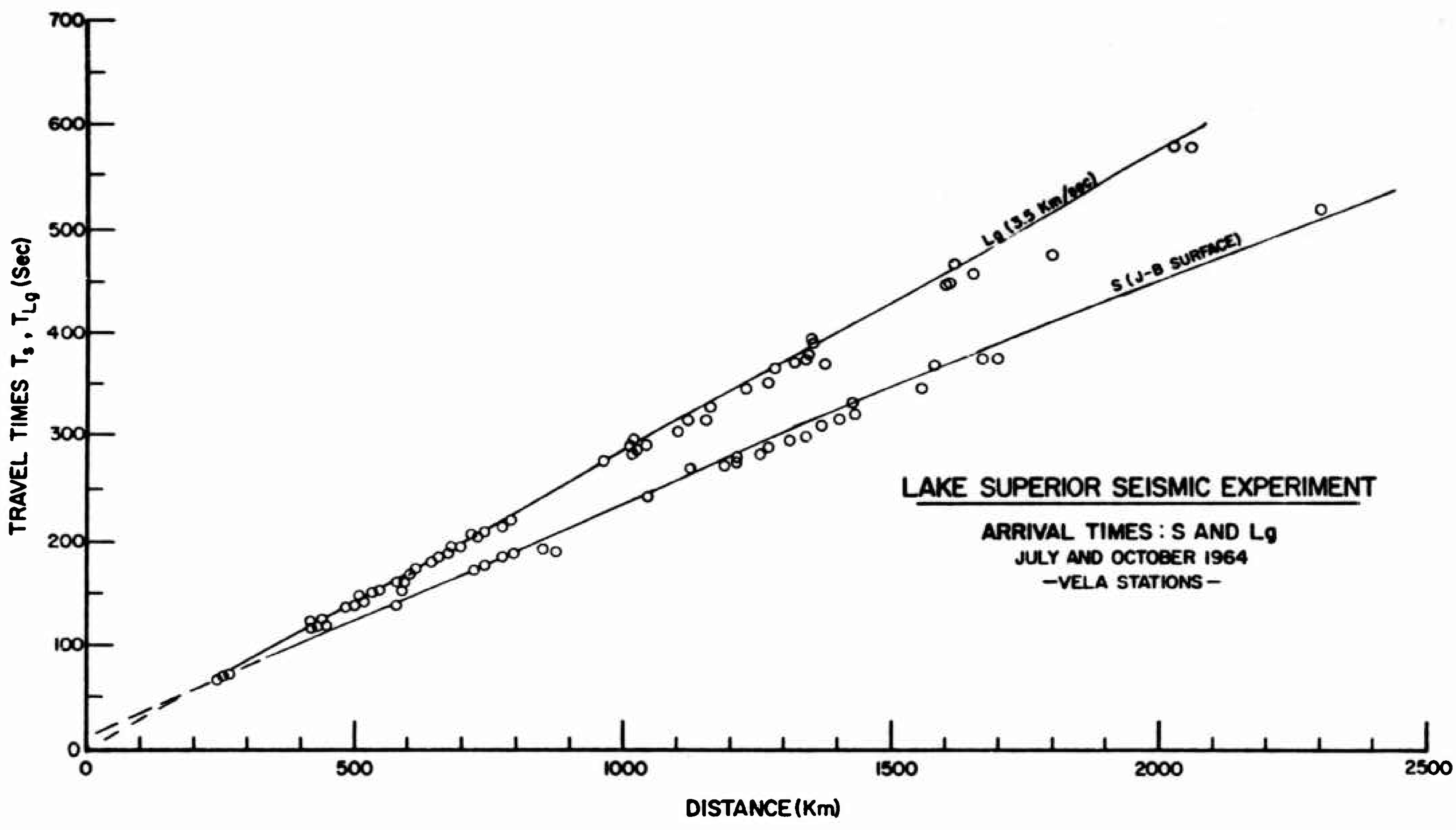
LAKE SUPERIOR SEISMIC EXPERIMENT

SHOTS OF 30 JULY 63

S & Lg MOTION ON SP VERTICAL AND
SP HORIZONTAL (RADIAL)

GI MA GLENDIVE, MONTANA

Figure 12
AFTAC/VSC



LAKE SUPERIOR SEISMIC EXPERIMENT
ARRIVAL TIMES : S AND Lg
JULY AND OCTOBER 1964
—VELA STATIONS—
Lg (3.5 Km/sec)
S (J-B SURFACE)
TRAVEL TIMES T_s , T_{Lg} (Sec)
DISTANCE (Km)
0
100
200
300
400
500
600
700
500
1000
1500
2000
2500

Figure 13
AFTAC/VSC

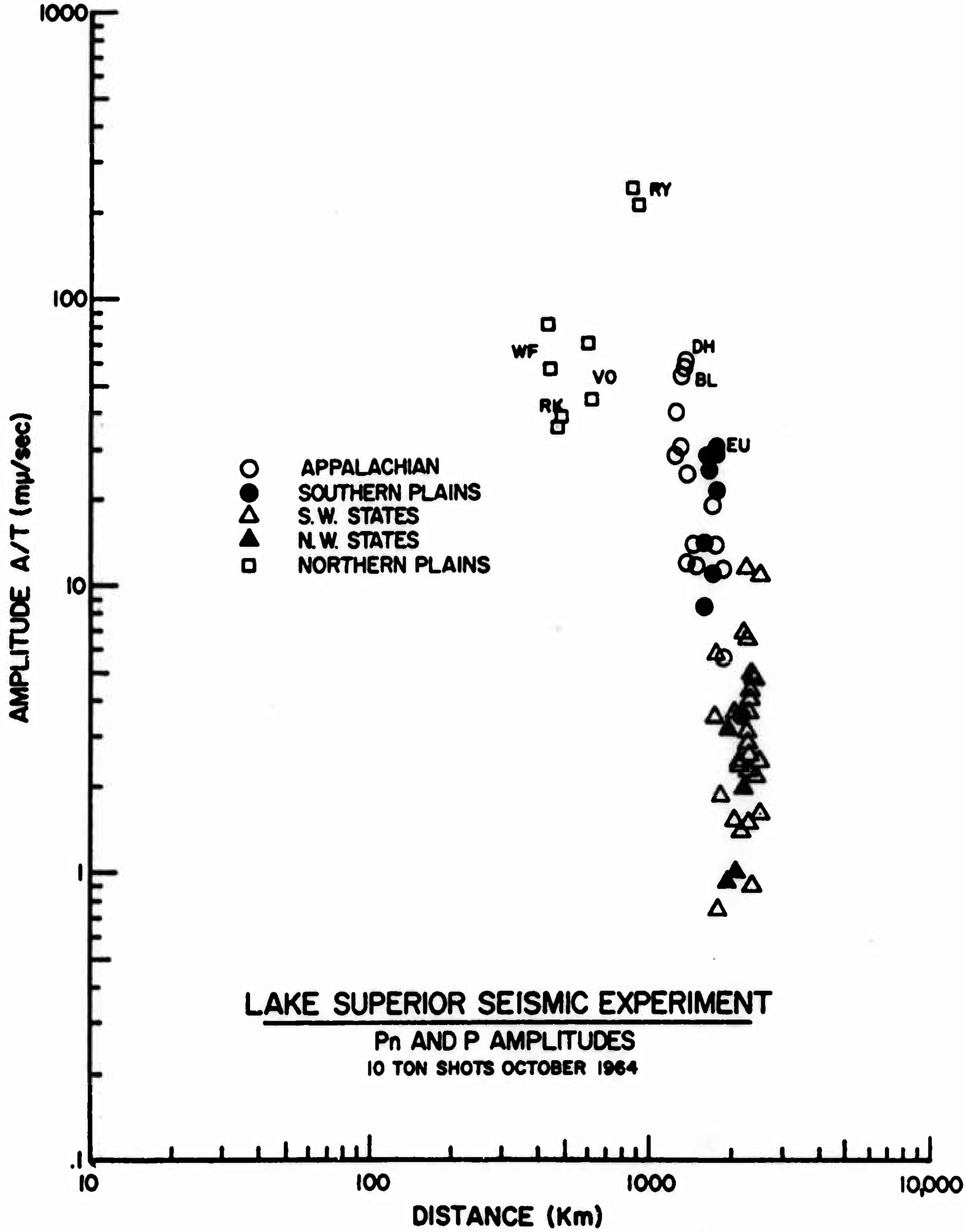


Figure 14
AFTAC/VSC

in the 200-1,300 km range there is some change in the nature of the paths of first-arrival signals because of complexities in the underlying layers. Our data beyond 1,300 km do not carry to a sufficient distance (2,600 km) to establish a well defined rate or rates of variation.

(4) The effect of explosive charge size on Pn and P amplitudes is shown in Figure 15. For several individual stations receiving signals from shots of more than one charge size, a composite plot is presented showing trends within the range from 250 lbs (1/8 ton) to 20,000 lbs (10 tons) of dynamite equivalent. Although there is not much continuity of data, it appears that a slope of approximately 1 is indicated, which is to say that the amplitude is directly proportional to the size of charge within the limits shown.

c. Amplitudes of S or Lg.

(1) As was indicated in the earlier discussion of travel times, Figure 13 gives evidence that both S and Lg signals were recorded at a number of stations. Owing to the emergent character of the signal maxima, only a few of the amplitude readings associated with these phases are definitely correlated to one or the other of these two types of motion. Four cases in which the readings could be clearly identified as to type of motion showed an average of 1.7 as the ratio of Lg and S amplitudes for the same events, as recorded on the same instrument component. The bulk of the recorded amplitudes were simply labeled (S or Lg) in the various graphs plotted.

(2) Figure 16 shows the (S or Lg) amplitudes for the two 10-ton shots previously discussed. The points show relatively little scatter,

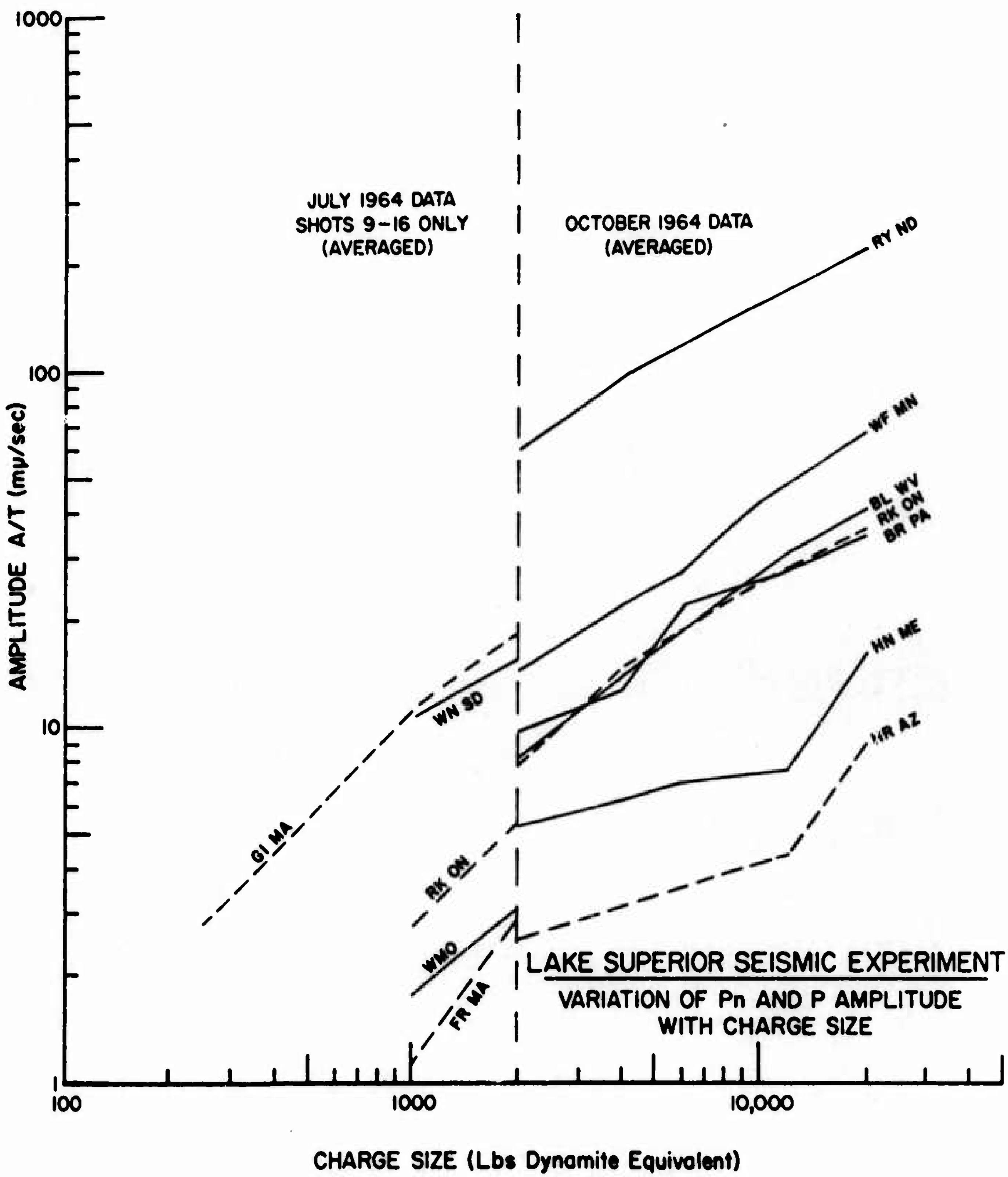


Figure 15
AFTAC/VSC

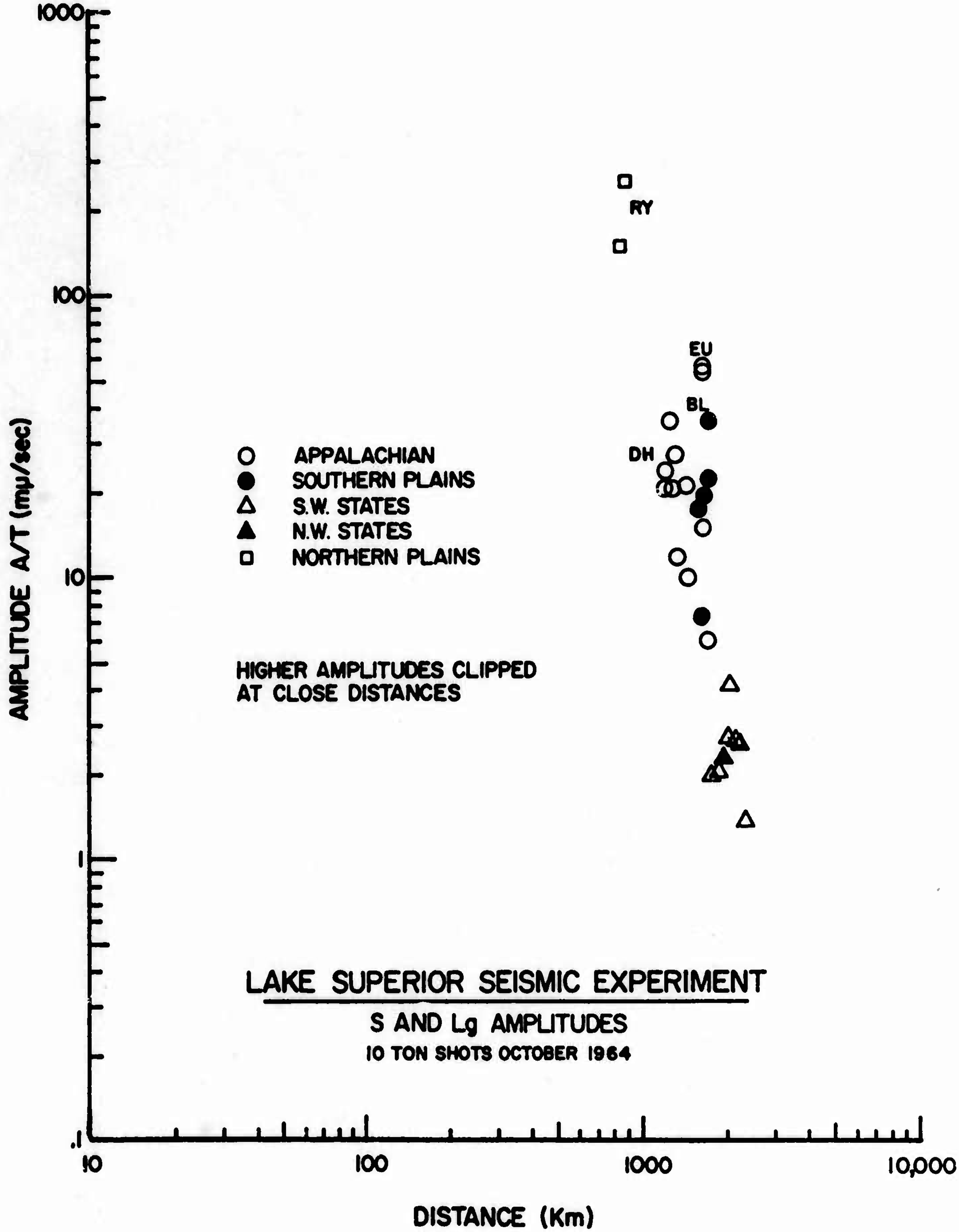


Figure 16
AFTAC/VSC

but no attempt is made to show a gradient in view of the uncertainty as to phase, as to regional signal level, and as to details of the transmission paths involved. Again the data shown is representative of a large number of readings from many weaker explosions.

(3) The variation of (S or Lg) amplitude with size of charge is shown in Figure 17. Again, several stations receiving signals from shots of more than one charge size are included, with lines connecting amplitudes received at a particular station from several sizes of shot. A composite effect again suggests that the amplitude is directly proportional to the size of explosive charge within the given limits.

d. Energy Considerations.

(1) Some comment should be made on the general question of how relatively small chemical explosions in Lake Superior managed to generate quite large signals to considerable distances. One shot of 1/8-ton size produced a measurable signal at Glendive, Montana (GI MA), at a distance of 1,128 km. A 1-ton shot was received at Seligman, Arizona (SG AZ), at a distance of 2,678 km. These somewhat unexpected results were in contrast to experience with explosion programs in the western United States and with quarry recordings further east.

(2) It seems likely that the signal strength is a combination of good coupling, signal augmentation, favorable instrument response, and efficient subcrustal energy transmission. Explosions in water or wet porous rock materials generally exhibit good coupling of the explosion to the ground. The present shot series, detonated on the lake bottom in

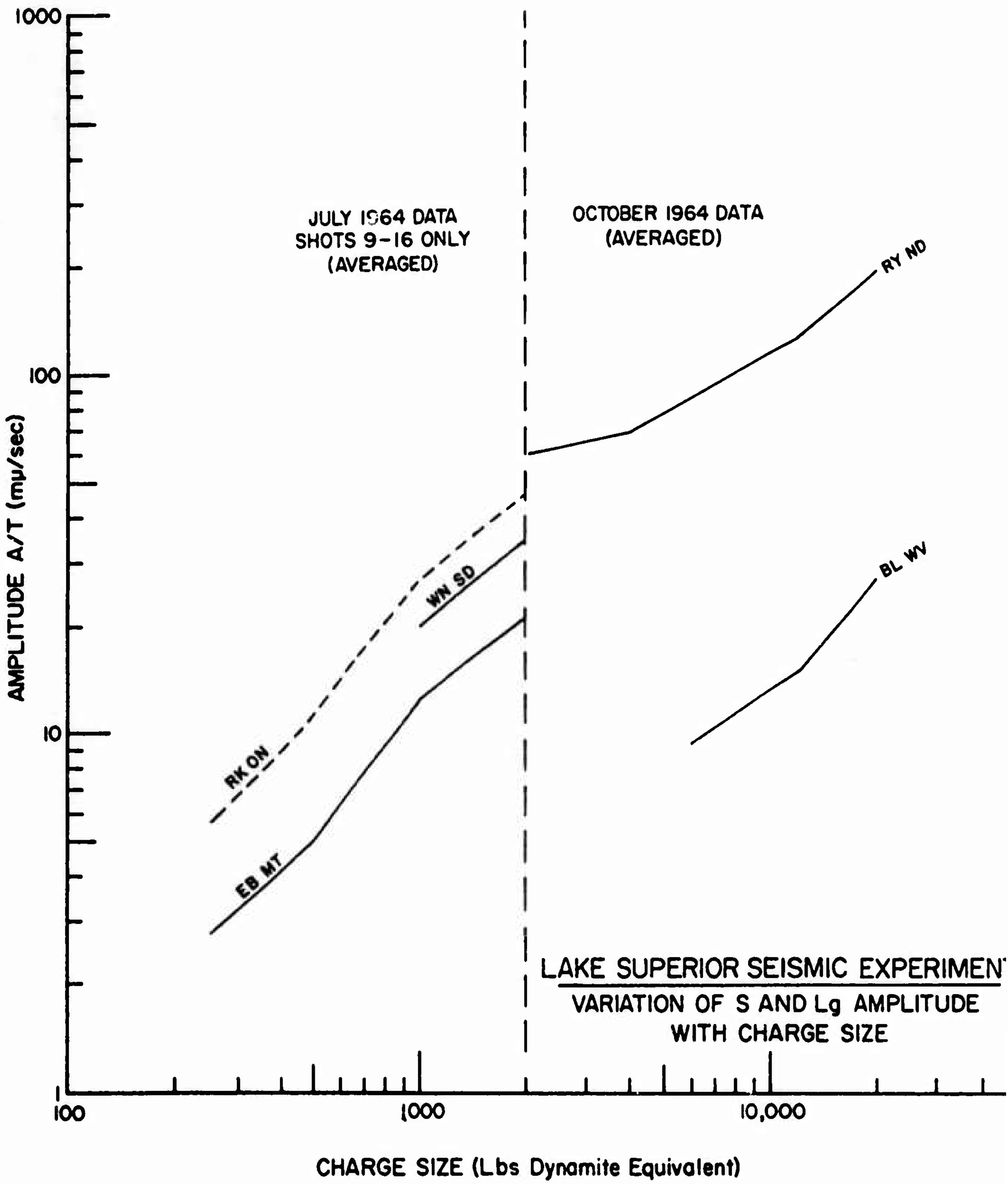


Figure
AFTAC/VS

depths as great as several hundred feet, were well coupled. Beyond this, it is usual for chemical explosions in water to be followed by oscillatory gas pocket pulses which carry considerable energy after the initial shock wave. Where the first gas bubble pulse collapses against the bottom, the oscillatory sequence is interrupted and additional seismic energy may be developed close behind the initial explosion shock wave within a time interval depending mainly on charge size and depth of water.

(3) The two 10-ton events yield computed magnitudes of approximately 3.7 in the western United States at teleseismic distances, a value that would appear anomalous without consideration of the water environment of the foci. As is indicated in the paper by D. E. Weston[1], explosions in water, if recorded in appropriate frequency ranges, may yield indicated magnitudes far above those for similar explosions in solid elastic media. The data for CHASE III[2], Lake Superior, and small high-explosive shots in water are all quantitatively consistent with the paper cited.

(4) Magnitude estimates of the 10-ton shots in the eastern United States range as high as 6.3 when the computations are conducted according to the procedures followed by VELA reports and the Coast and Geodetic Survey. These procedures are invalid for the eastern United States, owing to the fact that the dependence of A/T on epicenter distance generally shows very nearly a $1/r^2$ dependence from 150 to 2,200 km in this region. This conclusion can be confirmed either by a study of explosions (SS VILLAGE, GNOME, and SALMON) or of earthquakes of the eastern

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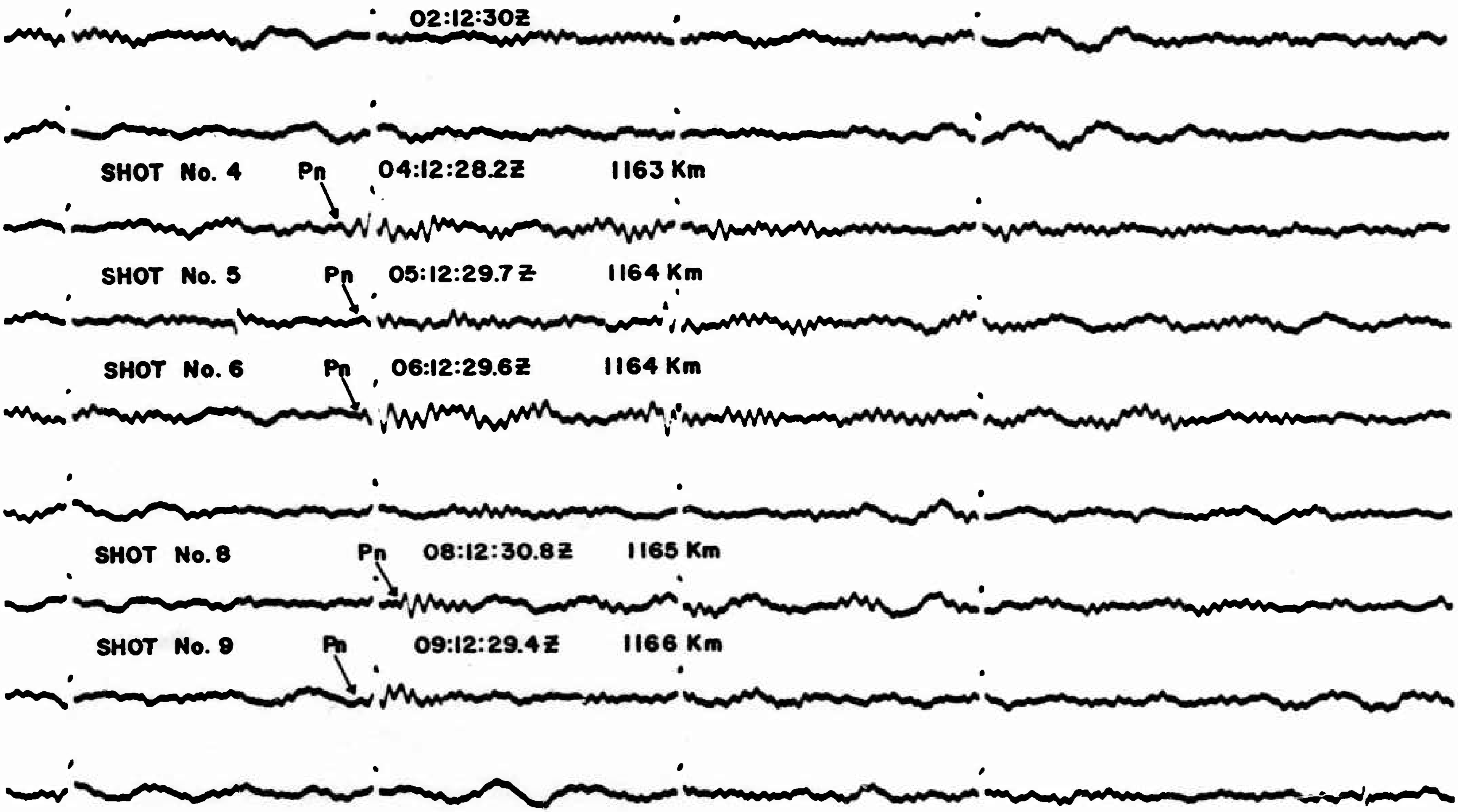
[1] "The Low Frequency Scaling Laws and Source Levels for Underground Explosions and Other Disturbances," Geophysical Journal of Royal Astronomical Society, Vol 3, pp 191-202 (1960).

[2] "Long Range Seismic Measurements, Project 8.4, CHASE III," Seismic Data Laboratory Report No. 124, Earth Sciences Division, Teledyne, Inc. (Formerly Teledyne Systems Company).

United States. When a scheme of magnitude predictions based on a study of events of the eastern United States is used, the 10-ton Lake Superior shots appear to be of magnitude 4.3, 0.7 above the value found at teleseismic distances. This discrepancy has yet to be explained, such a discrepancy between teleseismic and closer magnitude values not having been found for SS VILLAGE, CHASE III, GNOME, SALMON, or earthquakes of the eastern United States. It is in some manner related to the Lake Superior shot environment (explosions on bottom?).

e. Sample Signals. Several additional sample recordings are shown in Figures 18 through 22. The first three of these illustrate signals received at some of the eastern stations. Figure 21 shows a routine recording at TFO from a 1-ton lake shot. This may be contrasted with Figure 22, which is a recording of a 10-ton shot on the TFO northeast-southwest linear array. It may be seen on this illustration that there is a signal stepout of 1.2 sec for a linear distance of 10.5 km, so that the apparent arrival velocity of the P wave is 8.8 km/sec for a distance of 2,304 km at the array center. This is within the velocity range expected for this distance.

5. Conclusion. It may be said in general that the shot programs described have produced a large quantity of regional seismic information. Since the procedure is relatively simple and inexpensive it is likely that further programs will be developed. It appears that carefully planned projects using suitable station distribution and at least 5-ton charges might develop much additional useful information and that the utilization of other bodies of water might considerably extend existing geographical coverage.



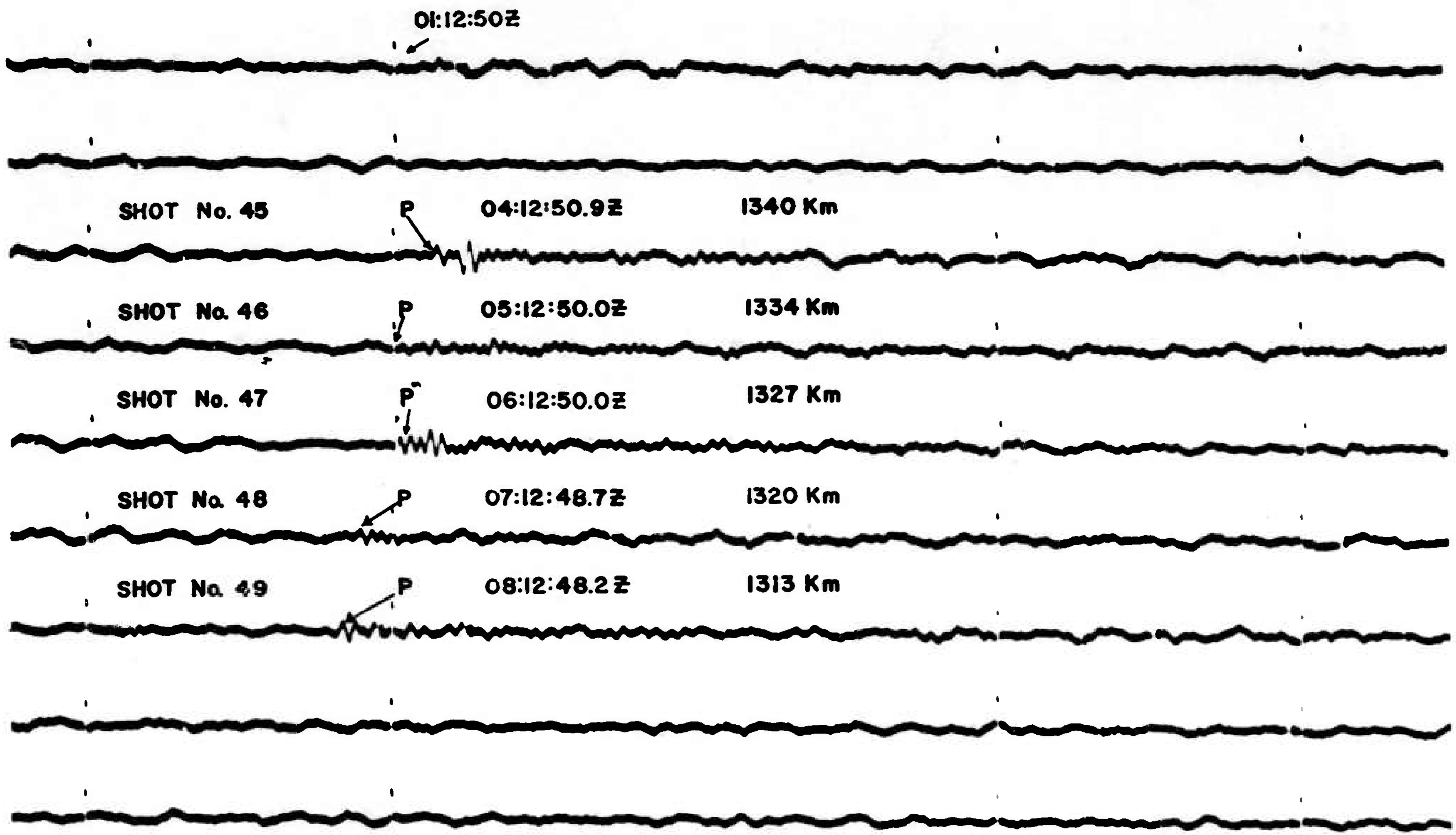
LAKE SUPERIOR SEISMIC EXPERIMENT

SHOTS OF 10 JULY 63

S–P VERTICAL—52.6 K (X10)

BL WV BECKLEY, WEST VIRGINIA

Figure 18
AFTAC/VSC



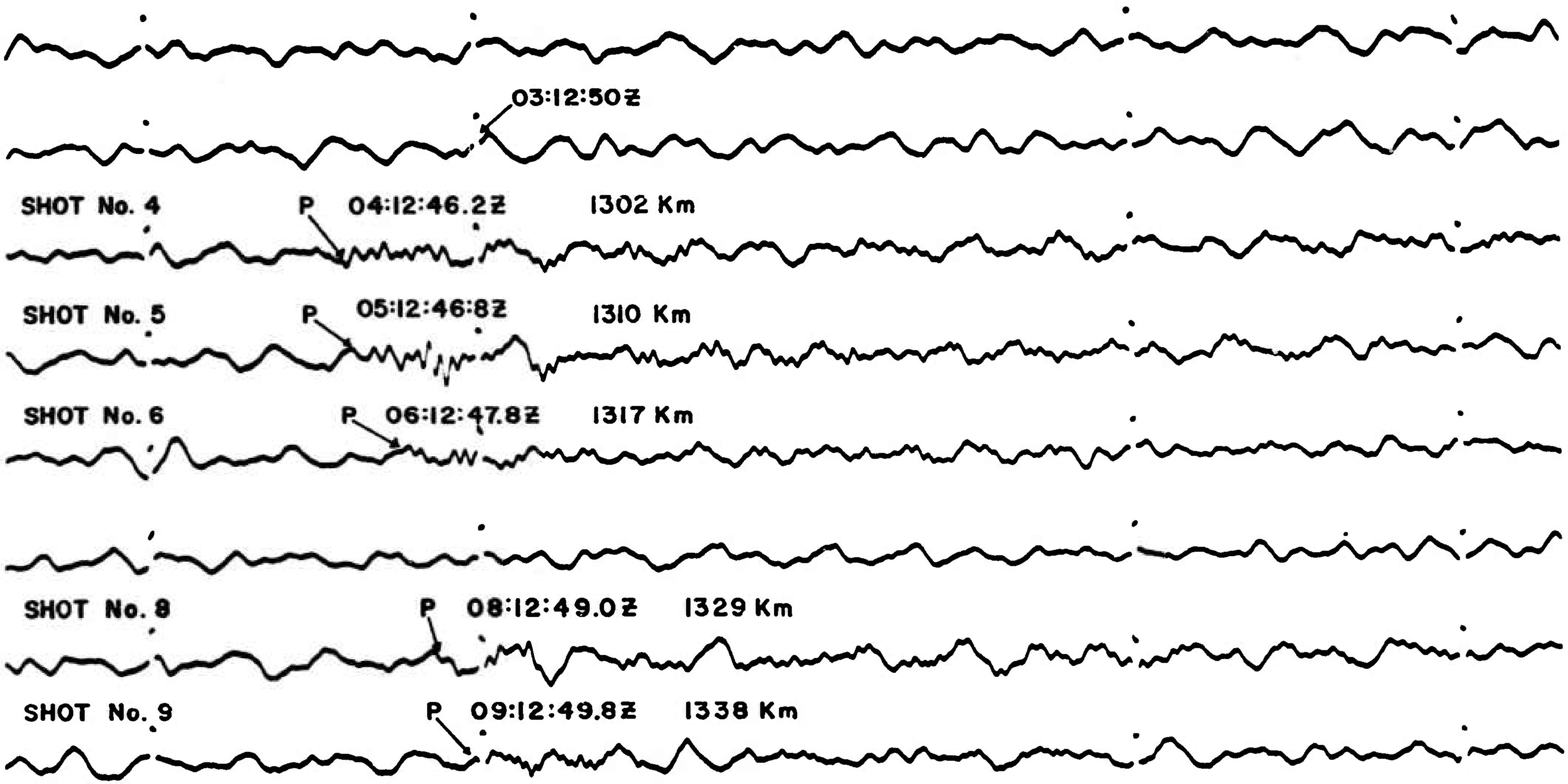
LAKE SUPERIOR SEISMIC EXPERIMENT

SHOTS OF 21 JULY 63

S-P VERTICAL—118.1 K (X10)

DH NY DELHI, NEW YORK

Figure 19
AFTAC/VSC



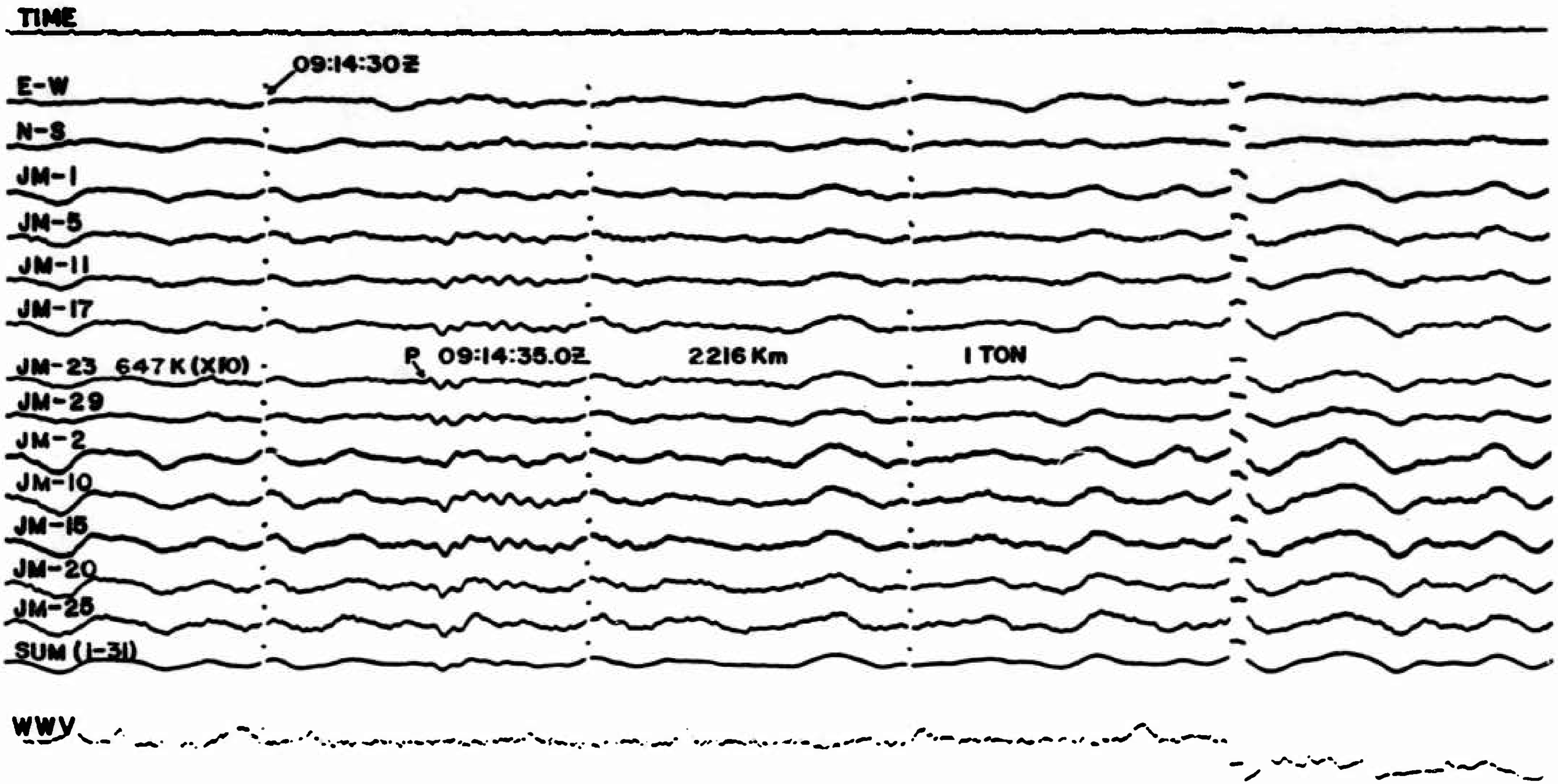
LAKE SUPERIOR SEISMIC EXPERIMENT

SHOTS OF 10 JULY 63

S-P VERTICAL—145.0 K (X10)

HN ME HOULTON, MAINE

Figure 20
AFTAC/VSC

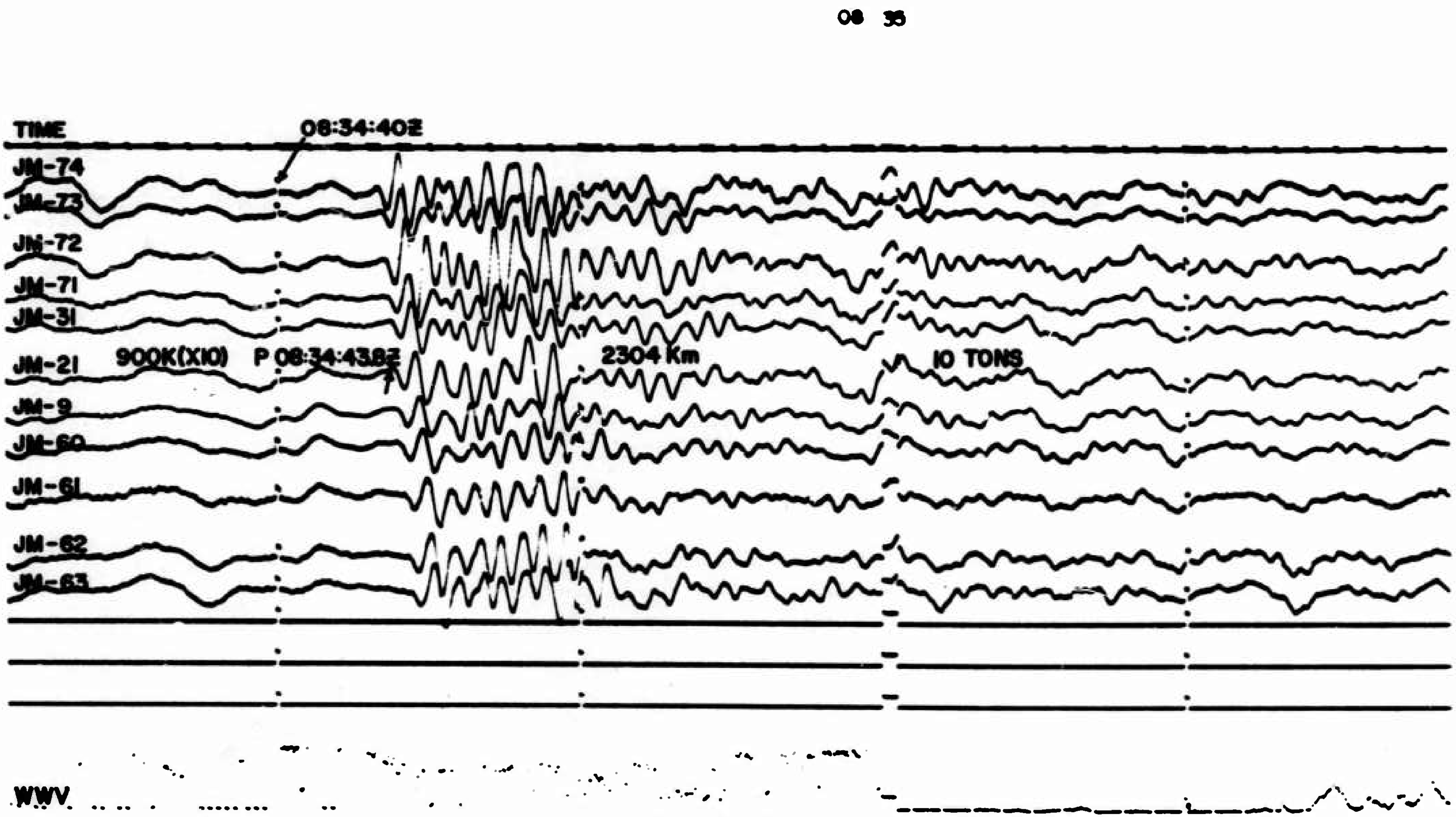


LAKE SUPERIOR SEISMIC EXPERIMENT

SHOT No. 34 17 JULY 63

TFO TONTO FOREST SEISMOLOGICAL OBSERVATORY, ARIZONA

Figure 21
AFTAC/VSC



LAKE SUPERIOR SEISMIC EXPERIMENT

SHOT No. 49 A 10 OCTOBER 64

P ARRIVAL

TFO TONTO FOREST SEISMOLOGICAL OBSERVATORY, ARIZONA

Figure 22
AFTAC/VSC